Stony Brook University

T2K

26th International Workshop on Weak Interactions and Neutrinos (2017)

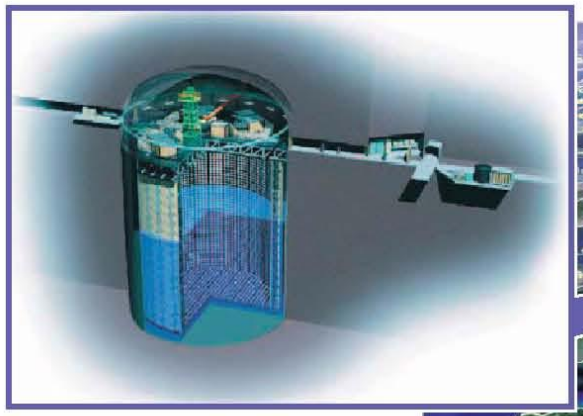
Latest Cross Section Results from T2K

Clark McGrew
Stony Brook Univ.
for the
T2K Collaboration

- A non-exhaustive summary of some recent results

The T2K Experiment

(Tokai-to-Kamioka)

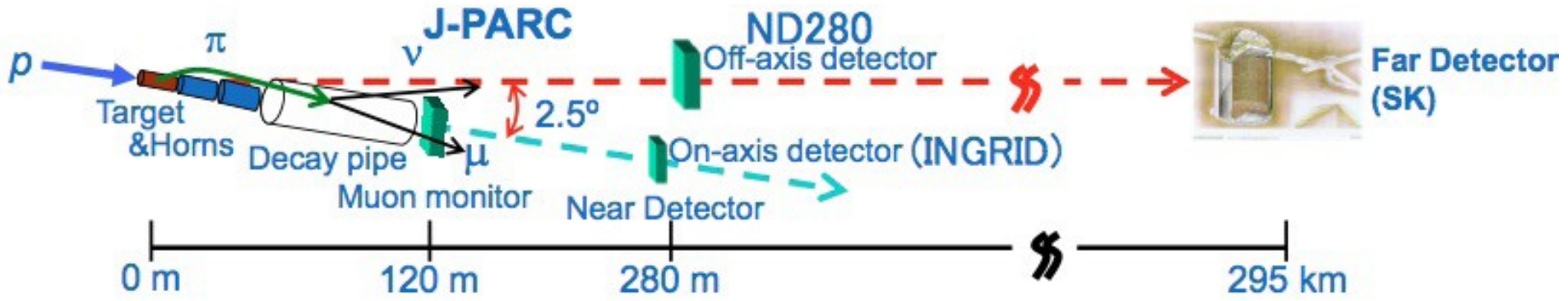


Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

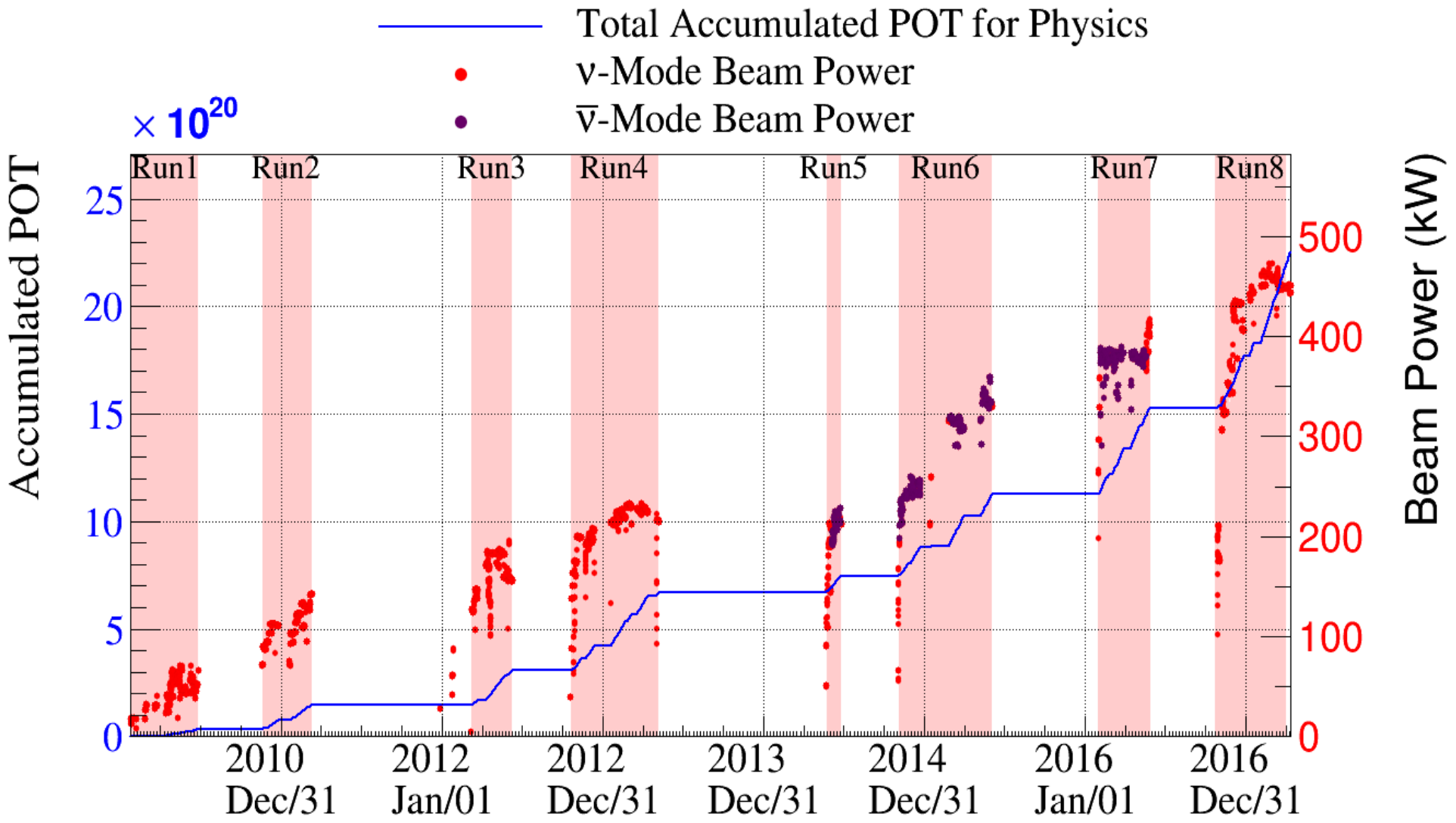
- Neutrino Oscillation Physics
  - Precise measurement of neutrino oscillation parameters: θ_{13}, θ_{23}, Δm^2_{31}, (δ_{CP})
    - Observe both appearance and disappearance channels
      - $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$, and $\nu_\mu \rightarrow \nu_\mu$
- Neutrino Cross-Section Physics (this presentation)

T2K Overview



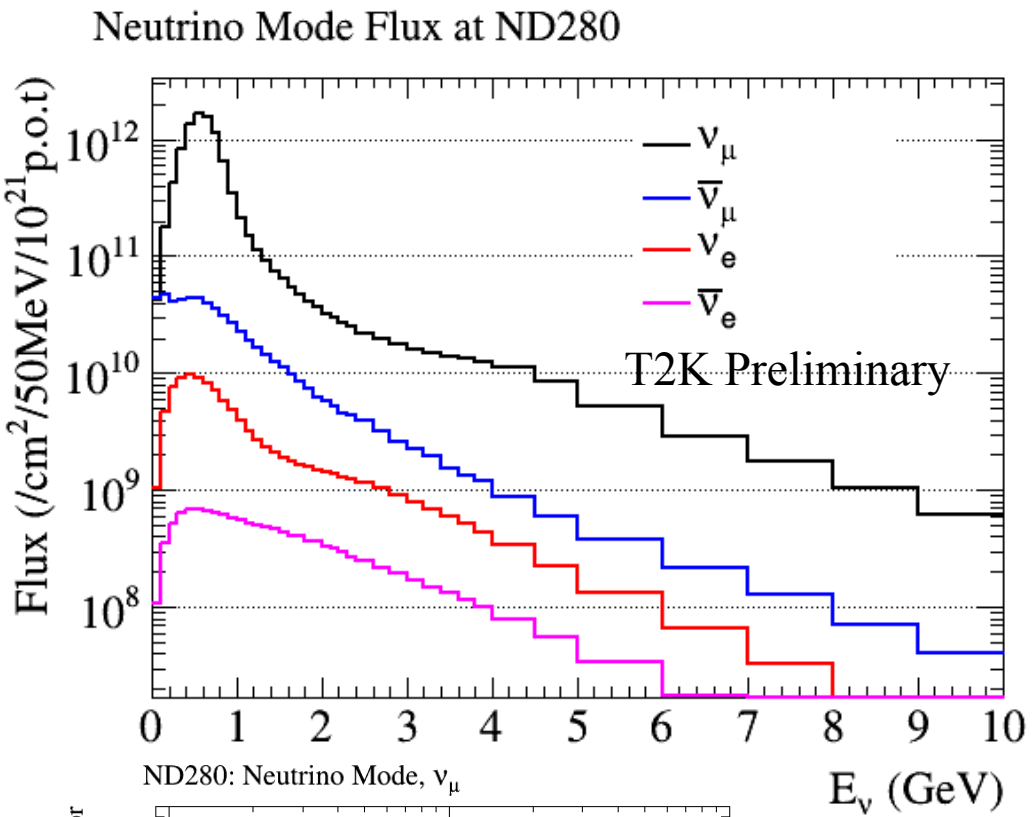
- High Power Accelerator
  - 30 GeV proton beam on 90 cm graphite target
  - Hadron production measured by CERN NA61/Shine
- Intense and High-Quality Neutrino Beam
  - Three magnetic horns focus sign-selected hadrons
- Secondary Beam Monitoring
  - Muon monitors behind beam dump: muon intensity and direction
- High-Resolution Near Detector at 280 m
  - INGRID on-axis: ν beam direction and intensity
  - ND280 off-axis: cross sections, ν beam spectrum, flux and flavor
- Far Detector at 295 km @ 2.5 degree off-axis
  - Super-Kamiokande: measure ν flux, spectrum and flavor

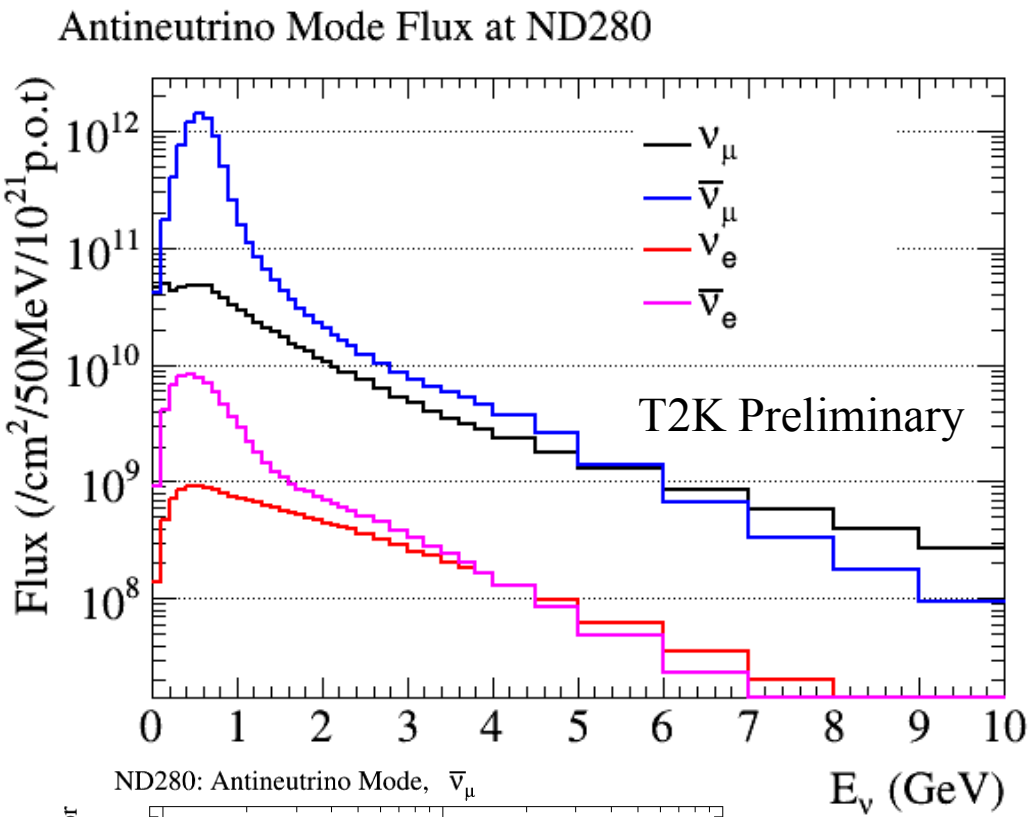
T2K Power and Protons on Target

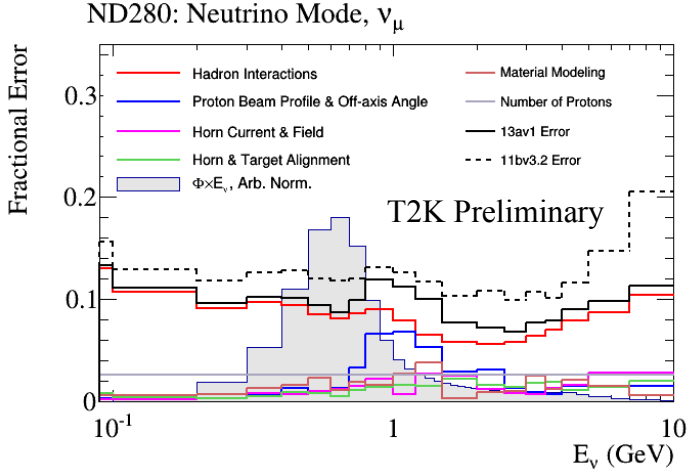


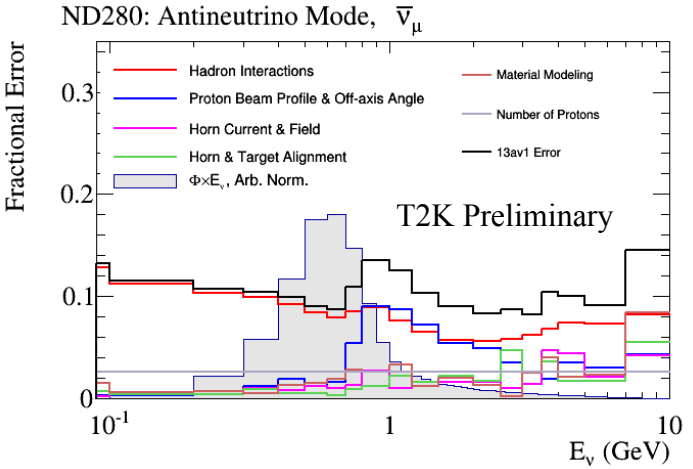
Doubled the accumulated neutrino mode protons on target during 2016 running

Fluxes at ND280 Detectors



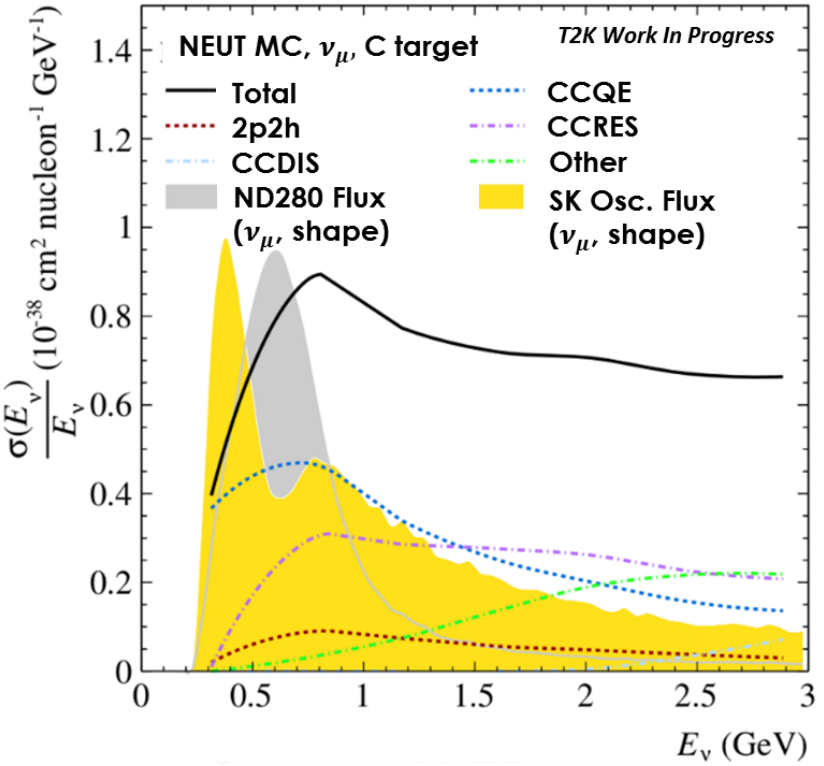




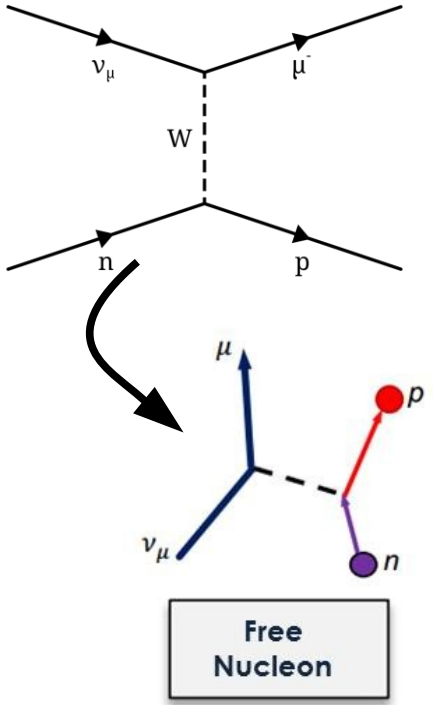


T2K Neutrino Interactions

Cross-section modeling contributes the largest systematic uncertainty to the oscillation analysis



Charged-Current Quasi-Elastic



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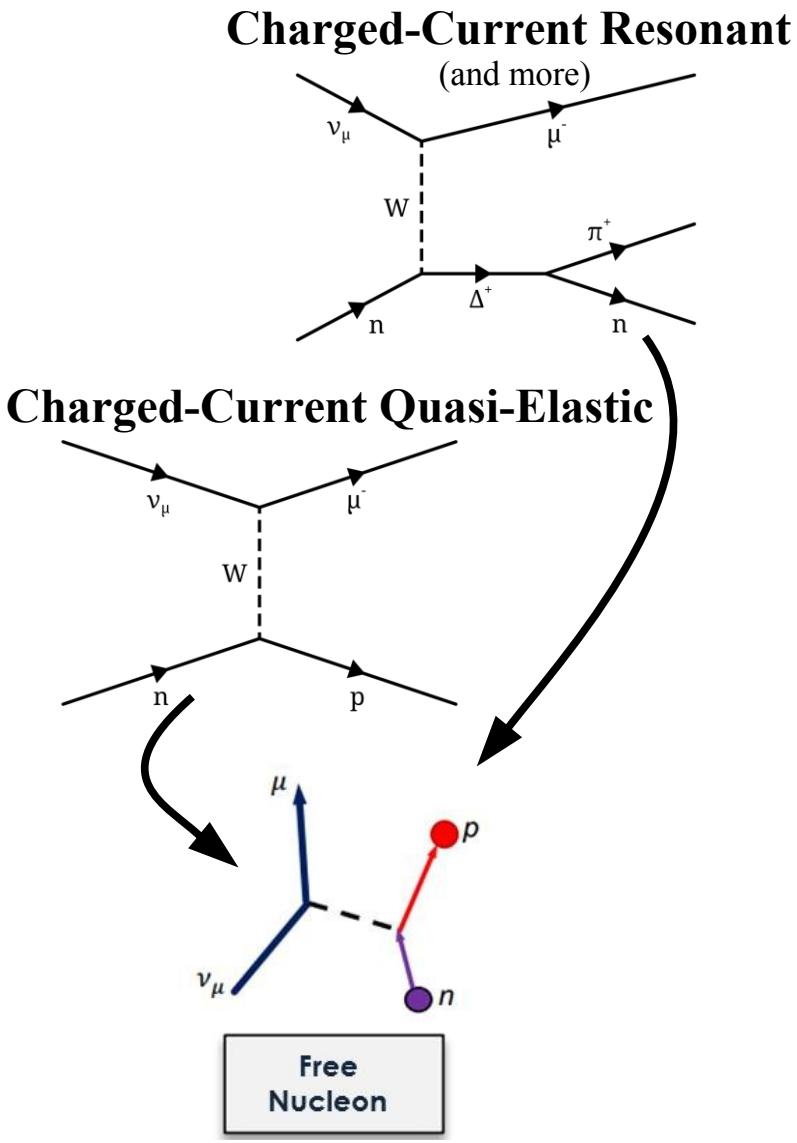

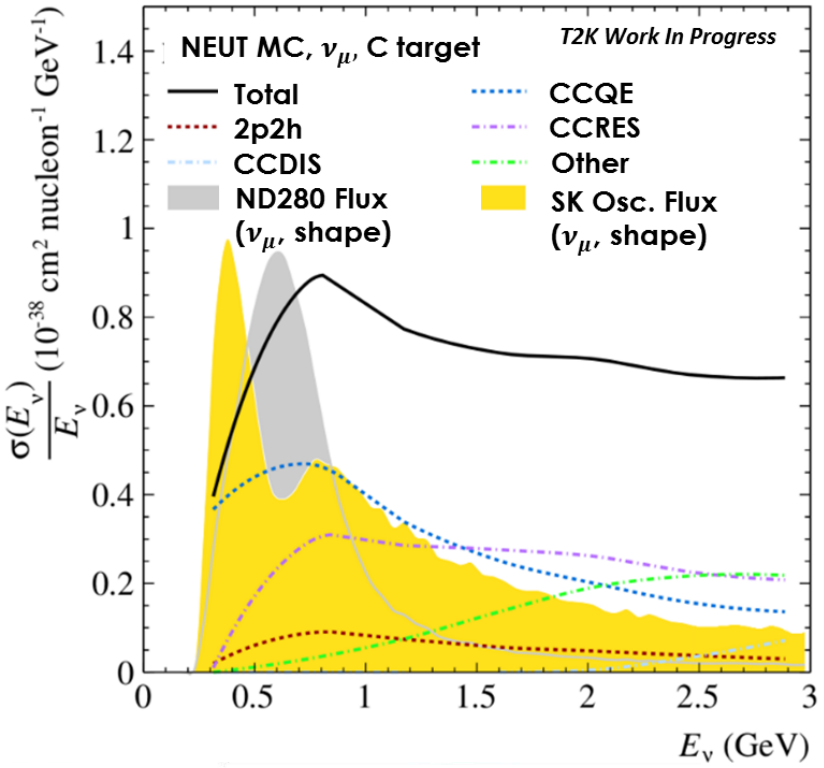

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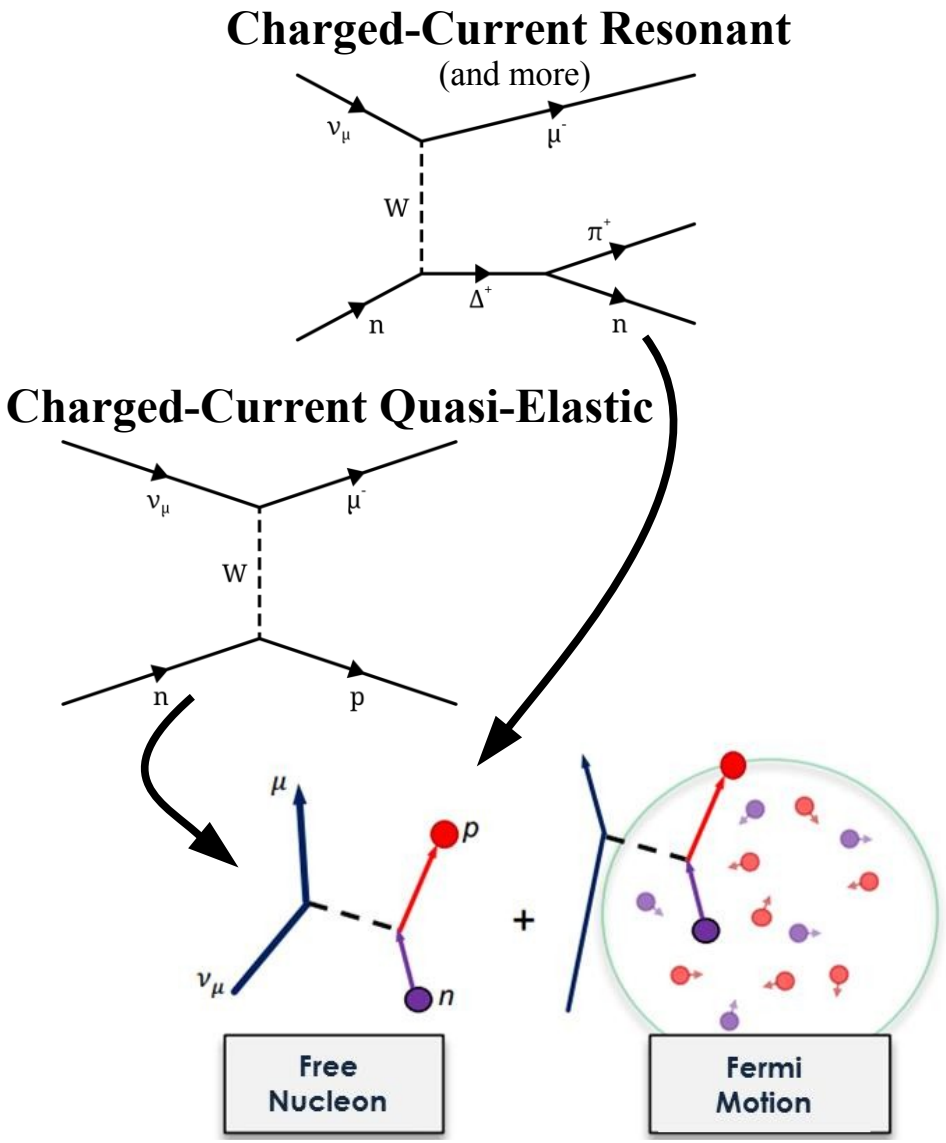
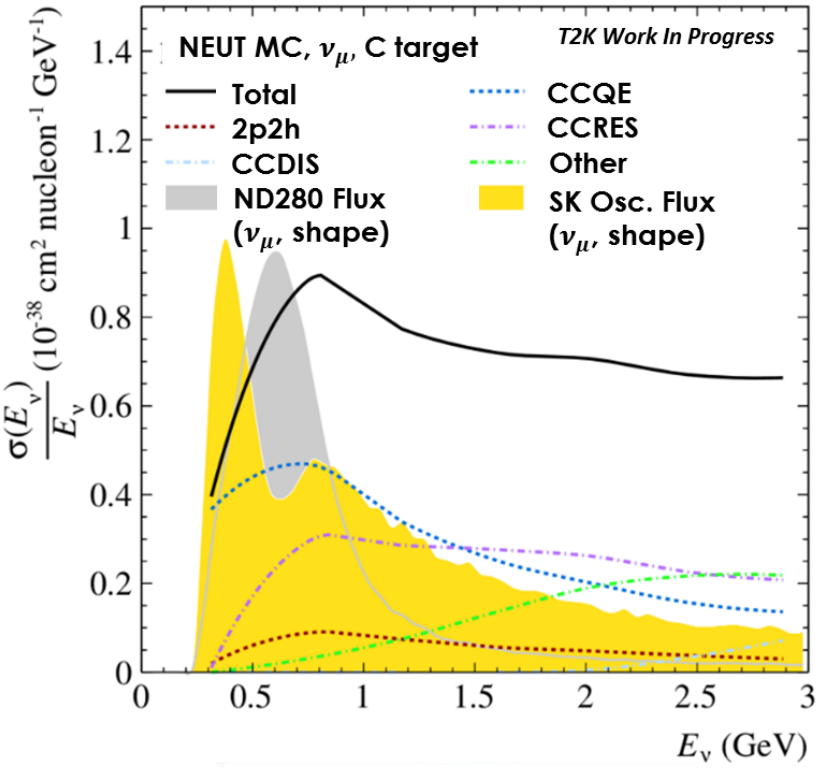


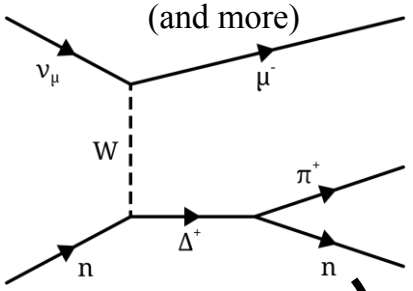


T2K Neutrino Interactions

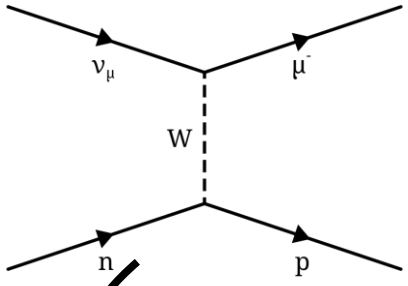
Cross-section modeling contributes the largest systematic uncertainty to the oscillation analysis

Charged-Current Resonant

(and more)

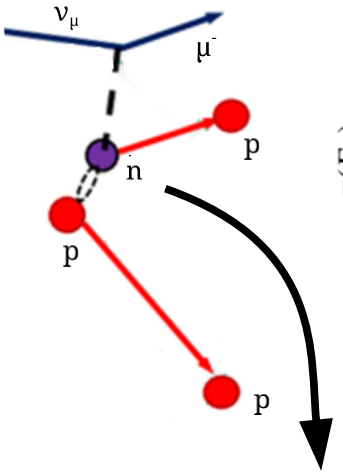


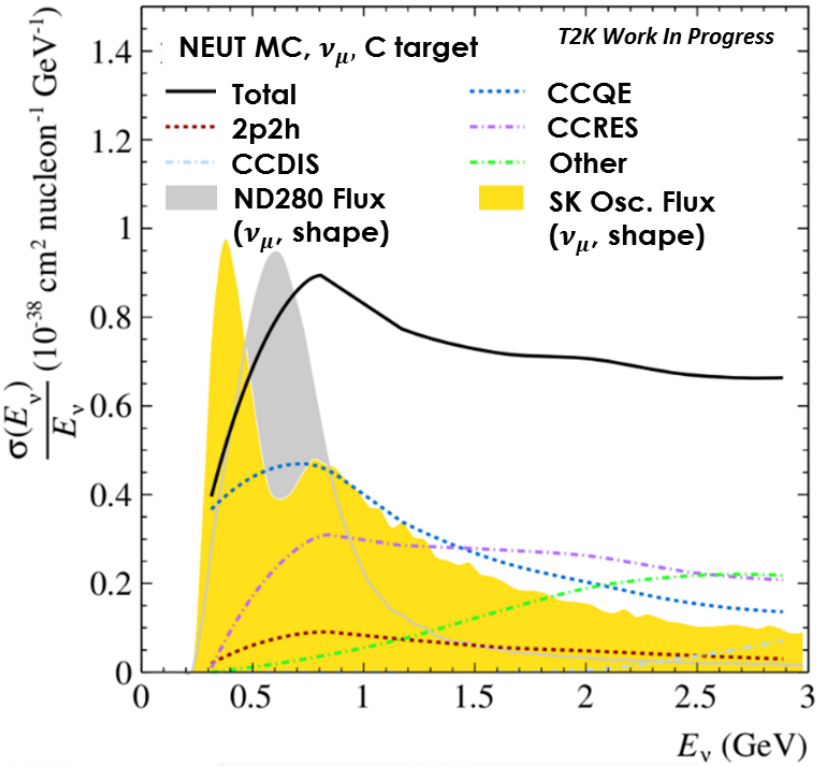
Charged-Current Quasi-Elastic

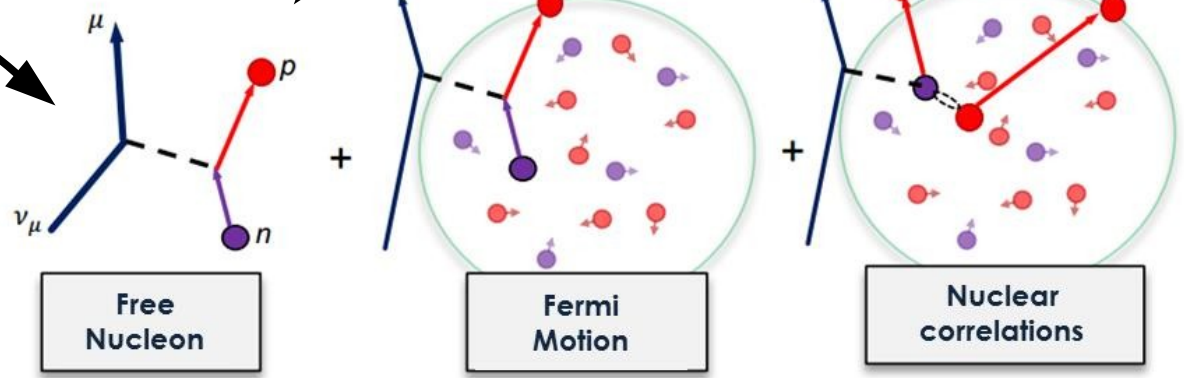


2p-2h

(2 particle – 2 hole)







T2K Neutrino Interactions

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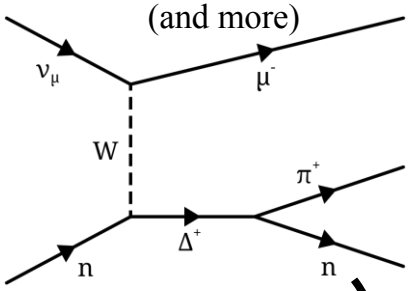

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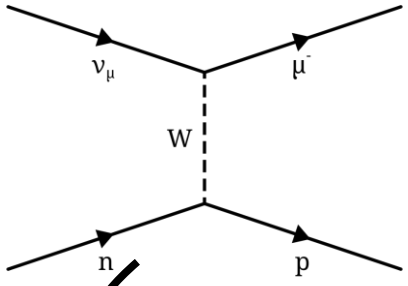

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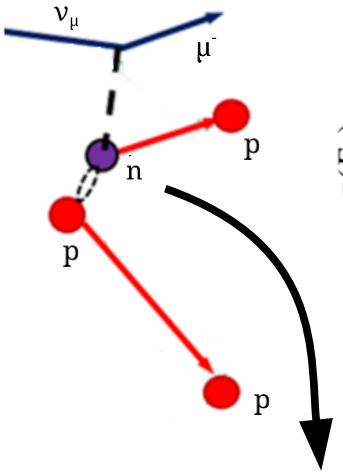
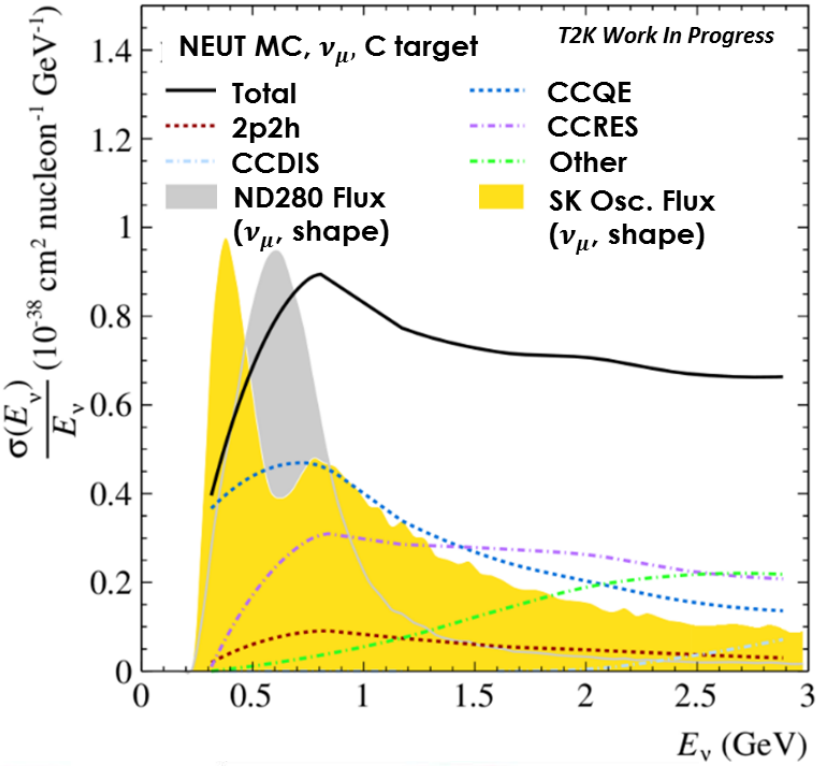
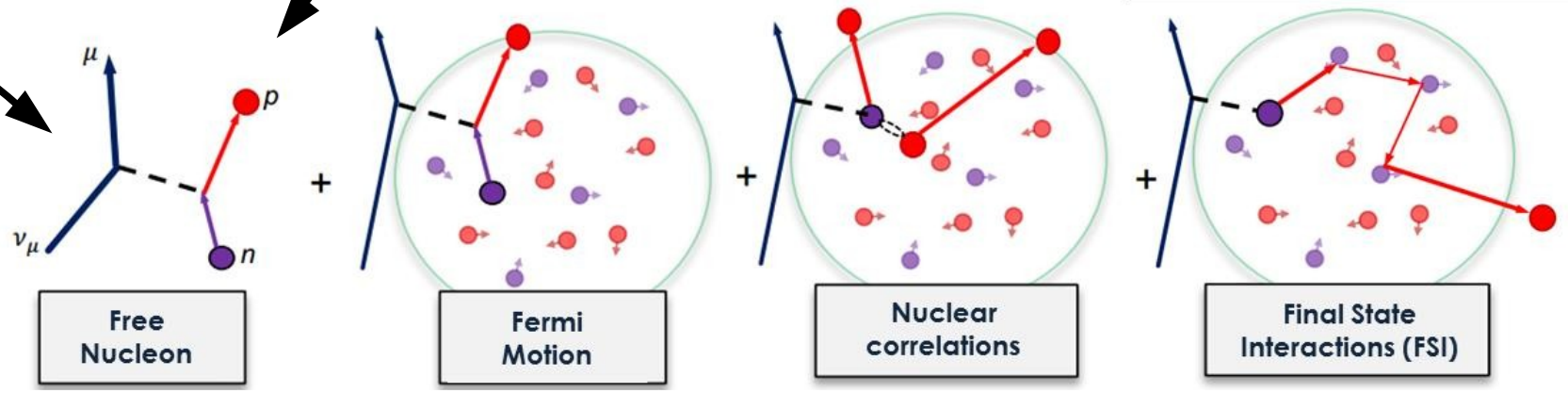


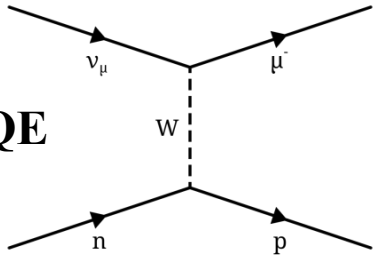




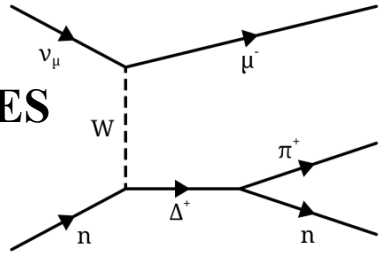
Neutrino Interactions vs Reconstructed Event Topology

Interaction Modes

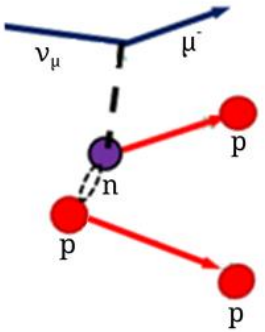
CCQE



CCRES



2p2h



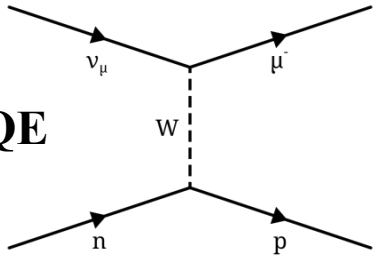
(+ more)

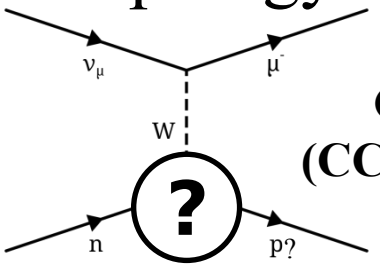
Neutrino Interactions vs Reconstructed Event Topology

Interaction Modes

Interaction Topology

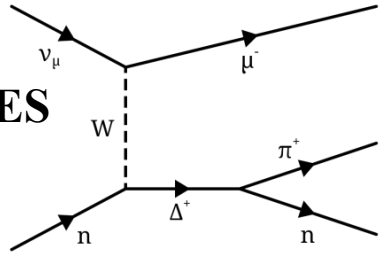
CCQE

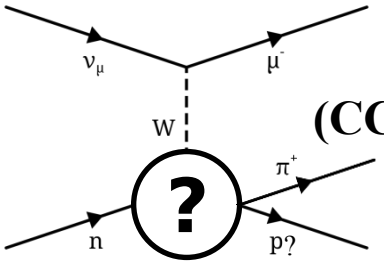




CC0π (CCQE-like)

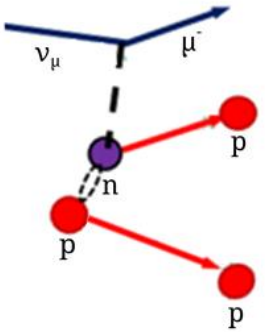
CCRES

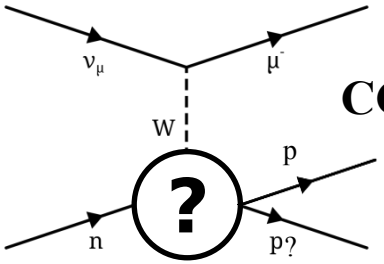




CC1π (CCRES-like)

2p2h





CC0π+Np (N>0)

(+ more)

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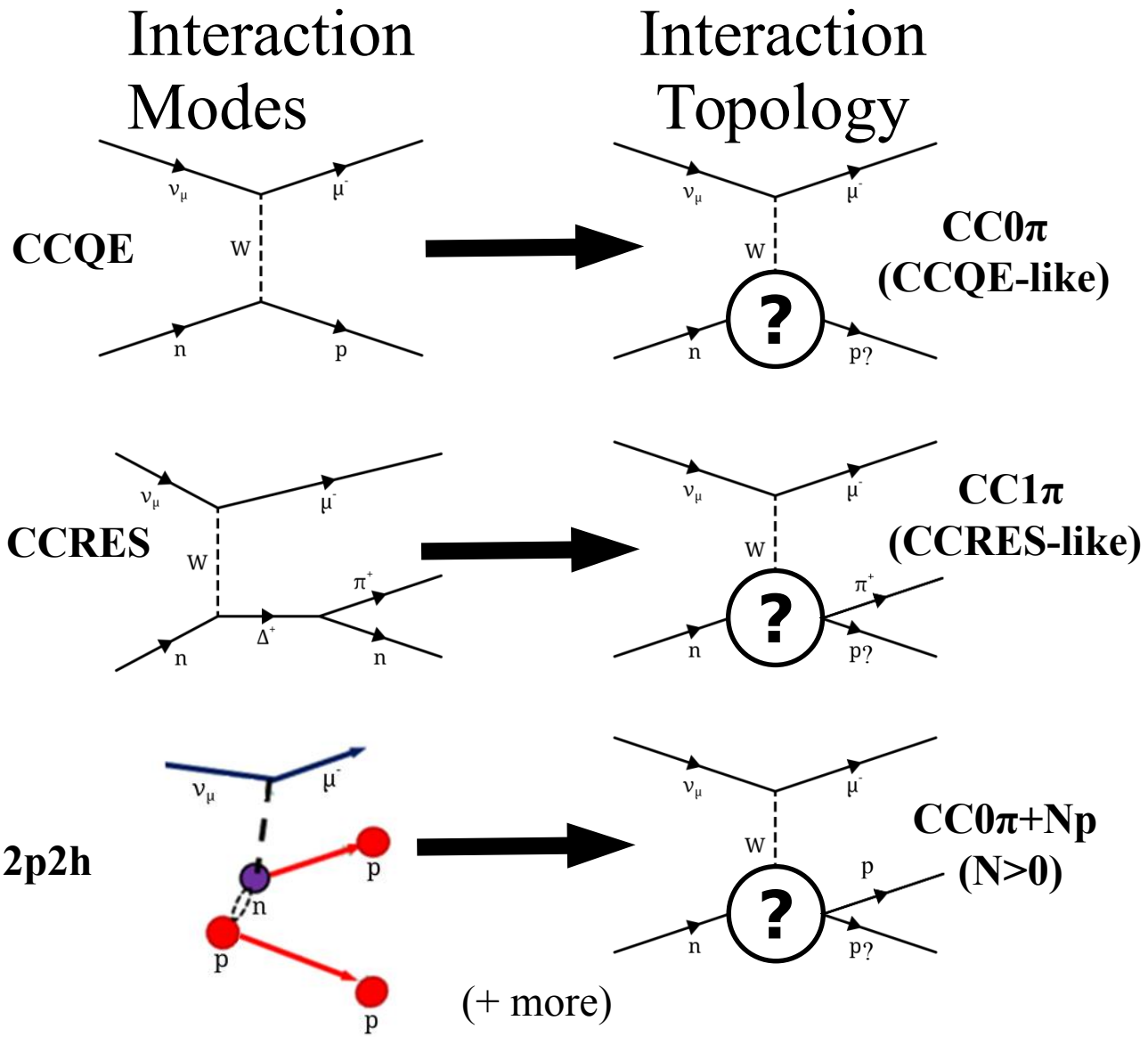

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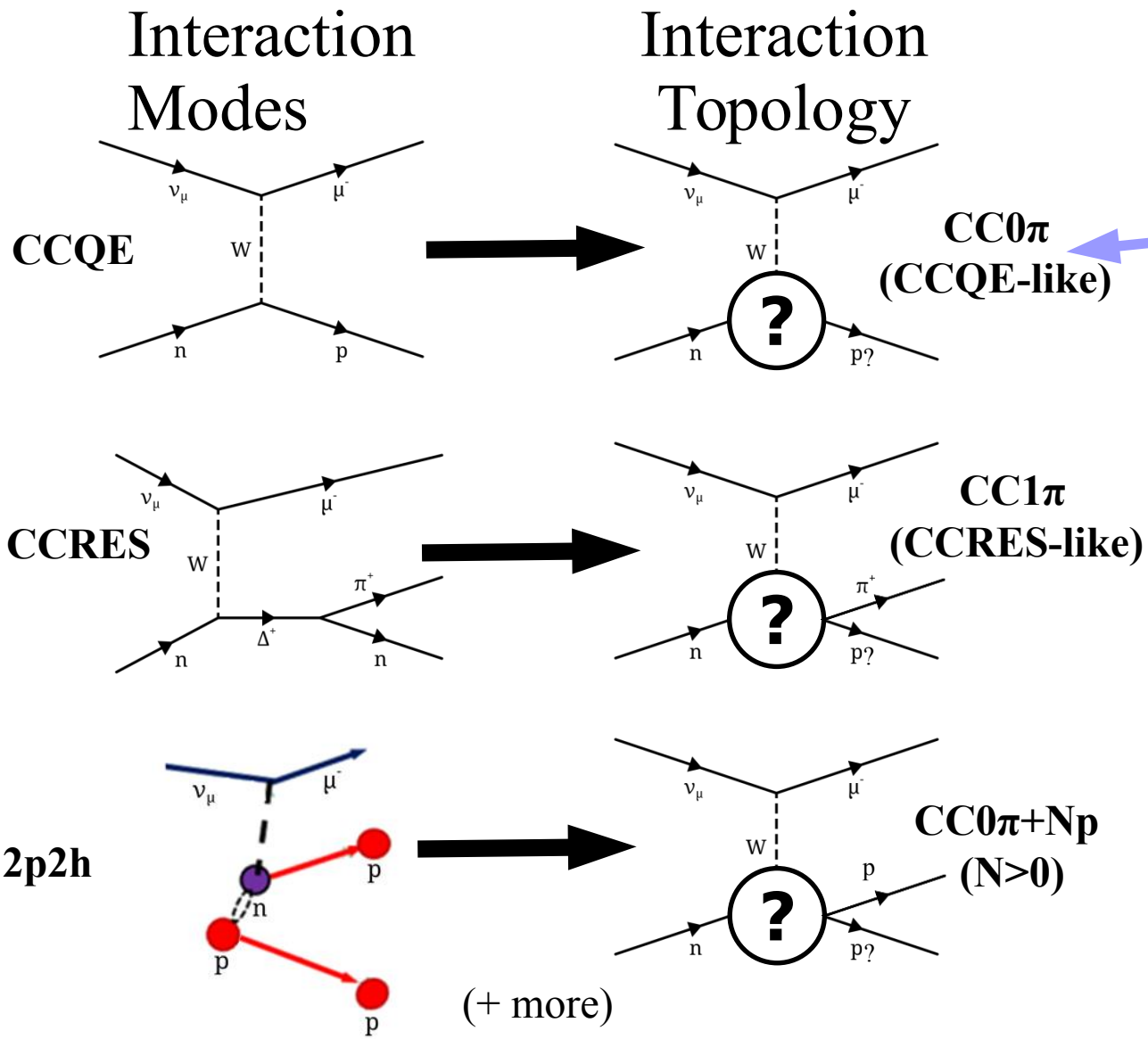
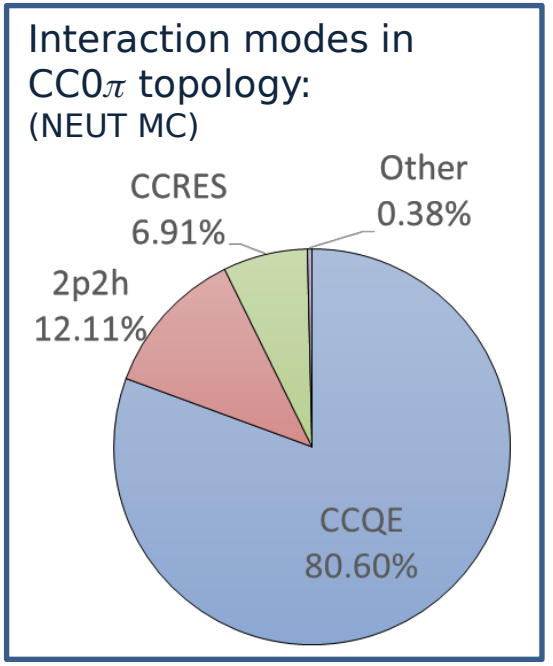




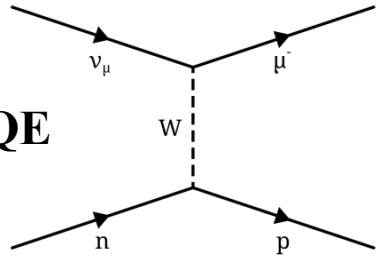
- Interaction masked by:
  - Nuclear Effects
  - Detector Response
  - &c
- Minimize model dependence by reporting event topologies

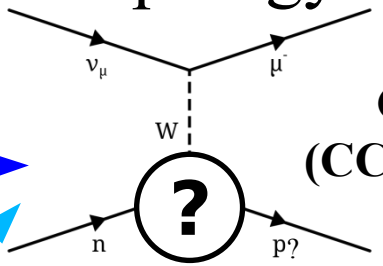
Neutrino Interactions vs Reconstructed Event Topology

Interaction Modes

Interaction Topology

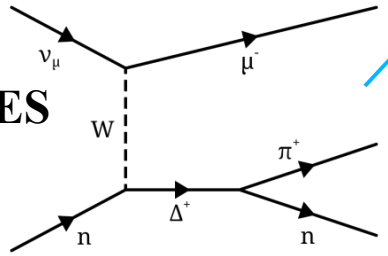
CCQE

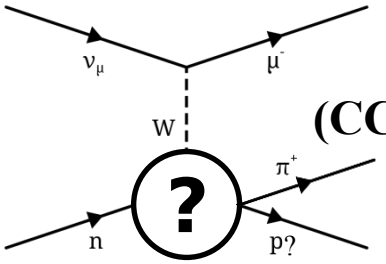




CC0π (CCQE-like)

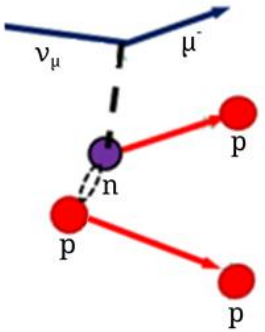
CCRES

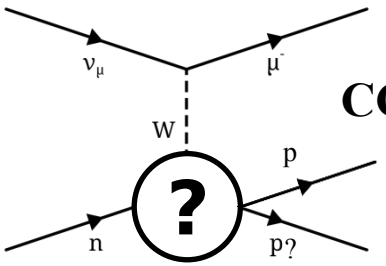




CC1π (CCRES-like)

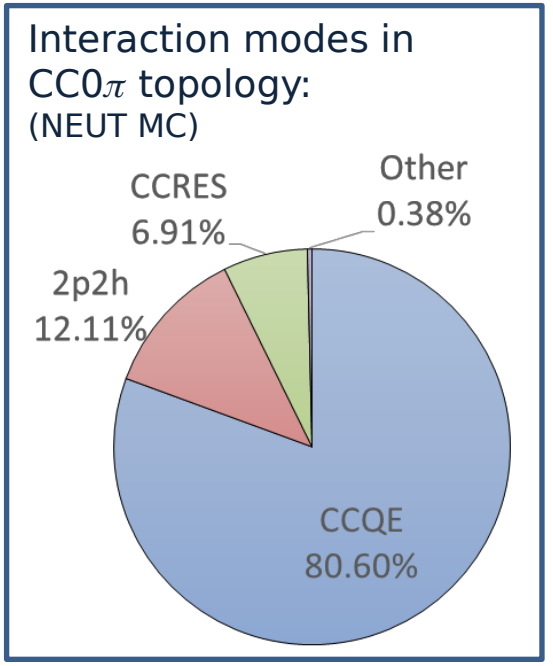
2p2h





CC0π+Np (N>0)

(+ more)



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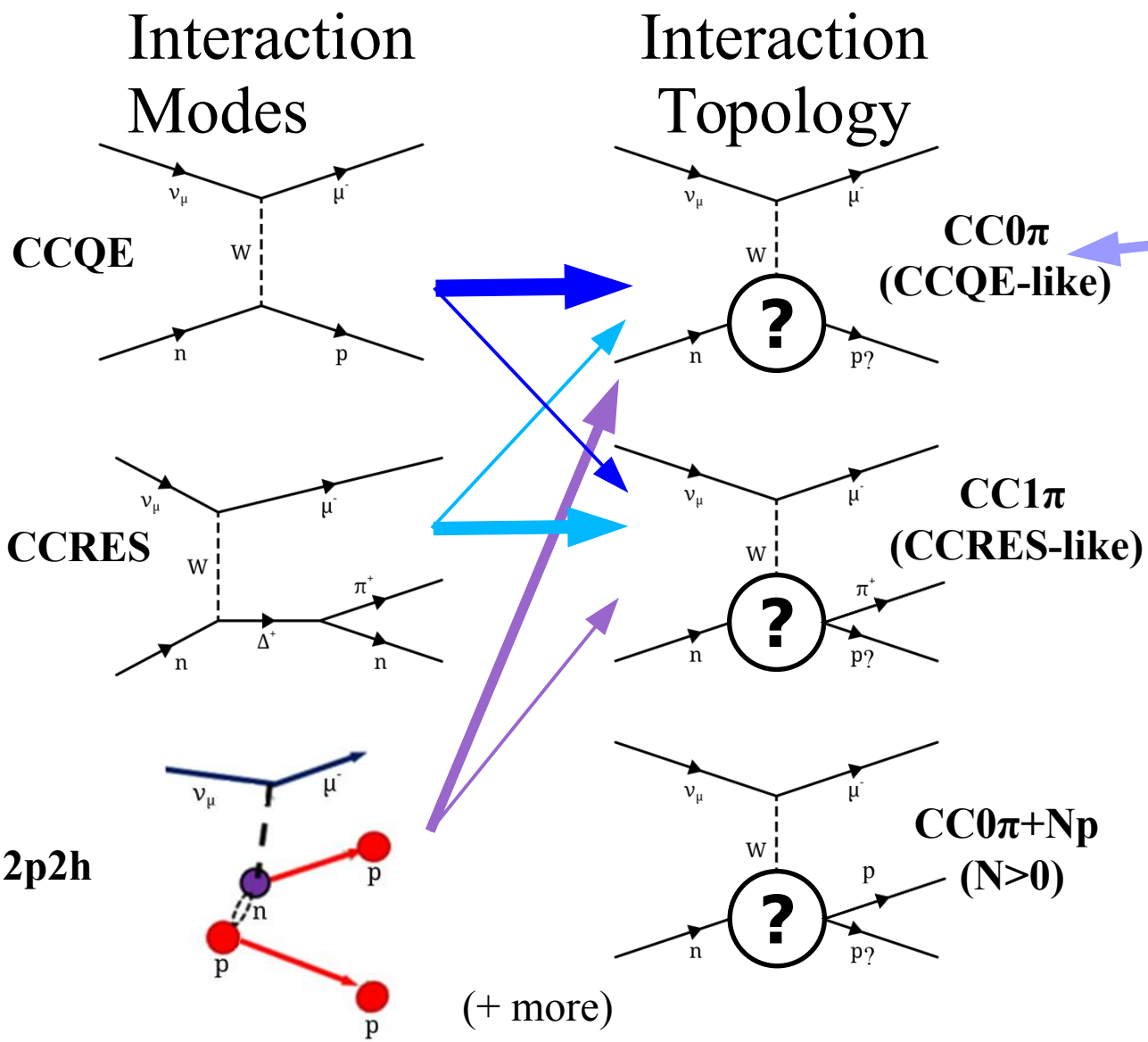
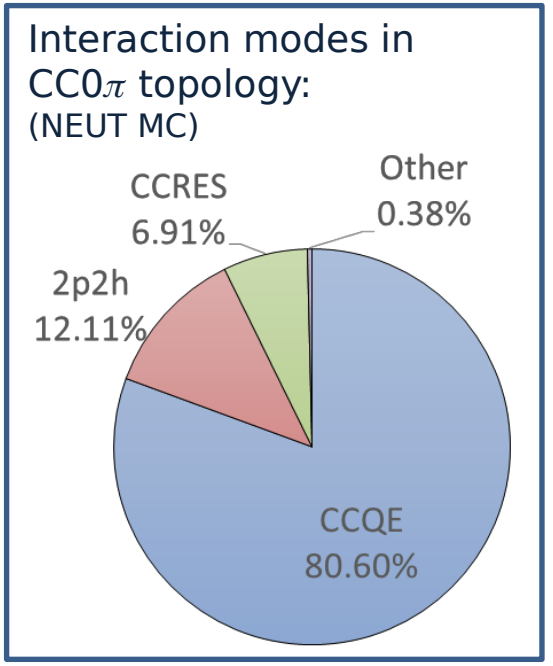
Neutrino Interactions vs Reconstructed Event Topology





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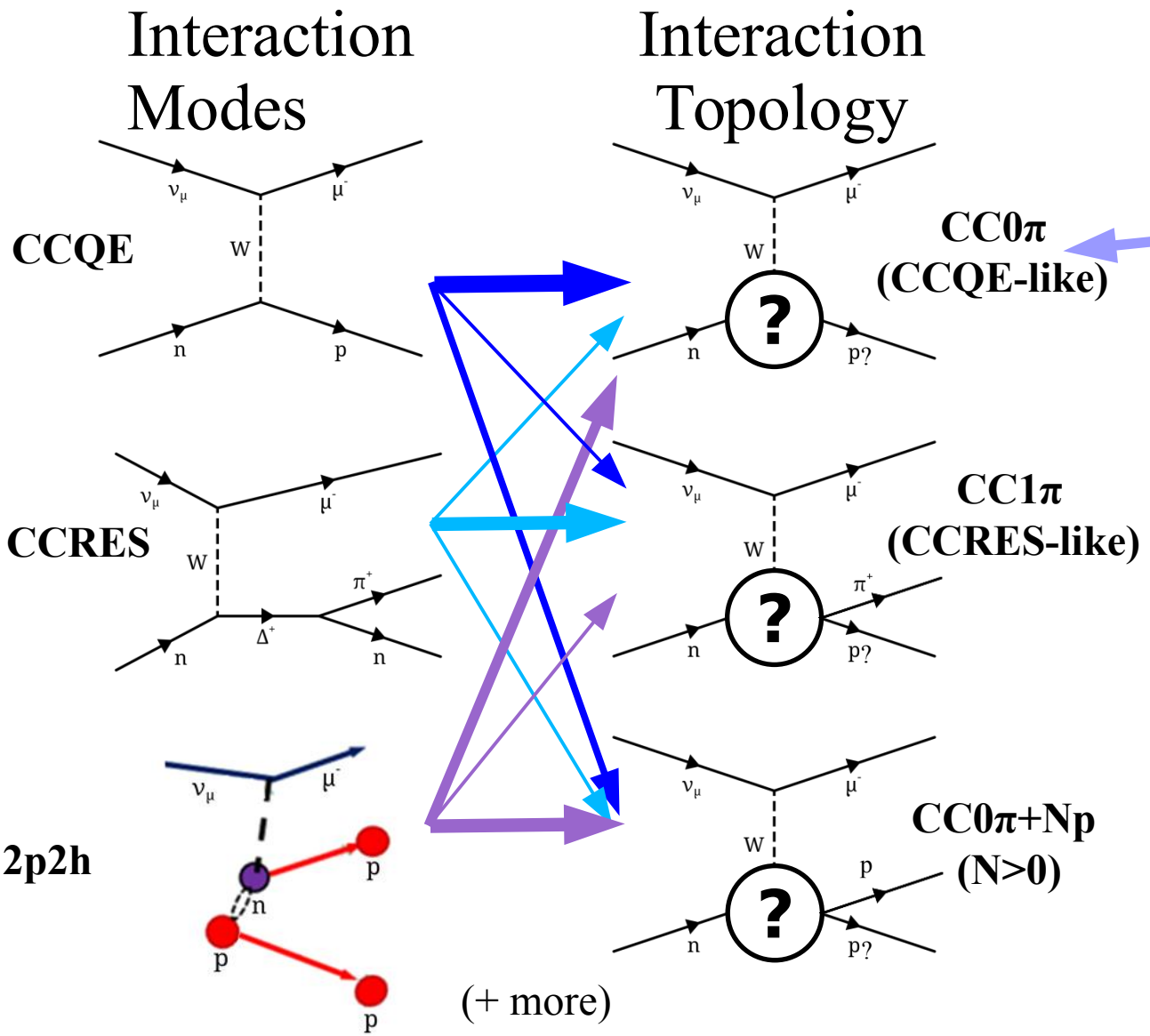

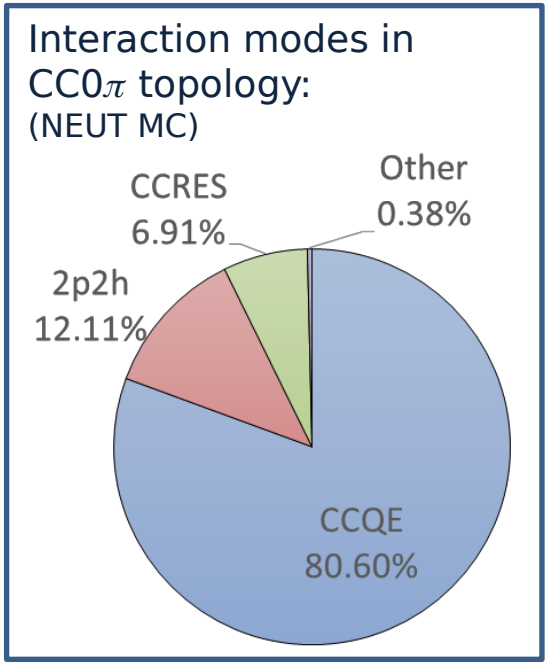

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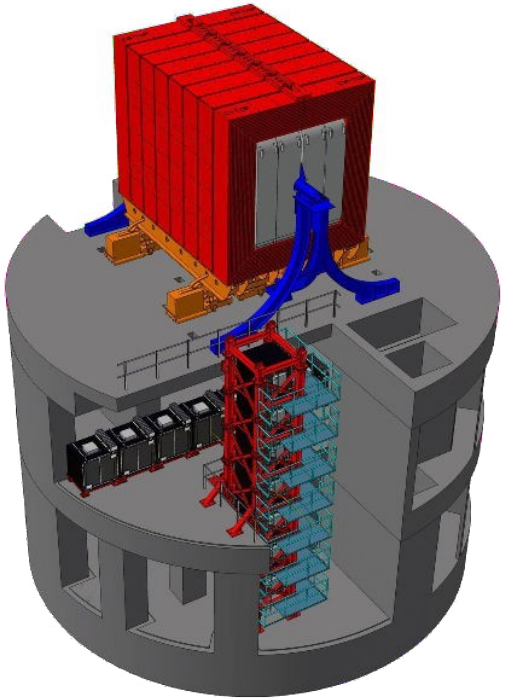
The ND280 Detectors

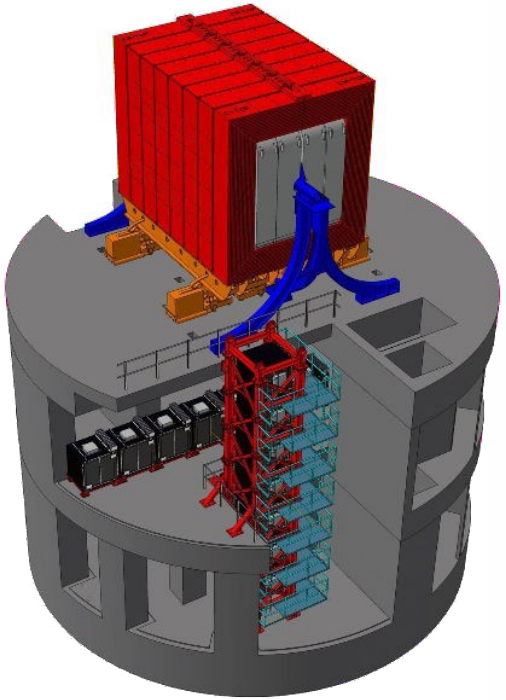
(**N**ear **D**etectors @ **280** Meters)

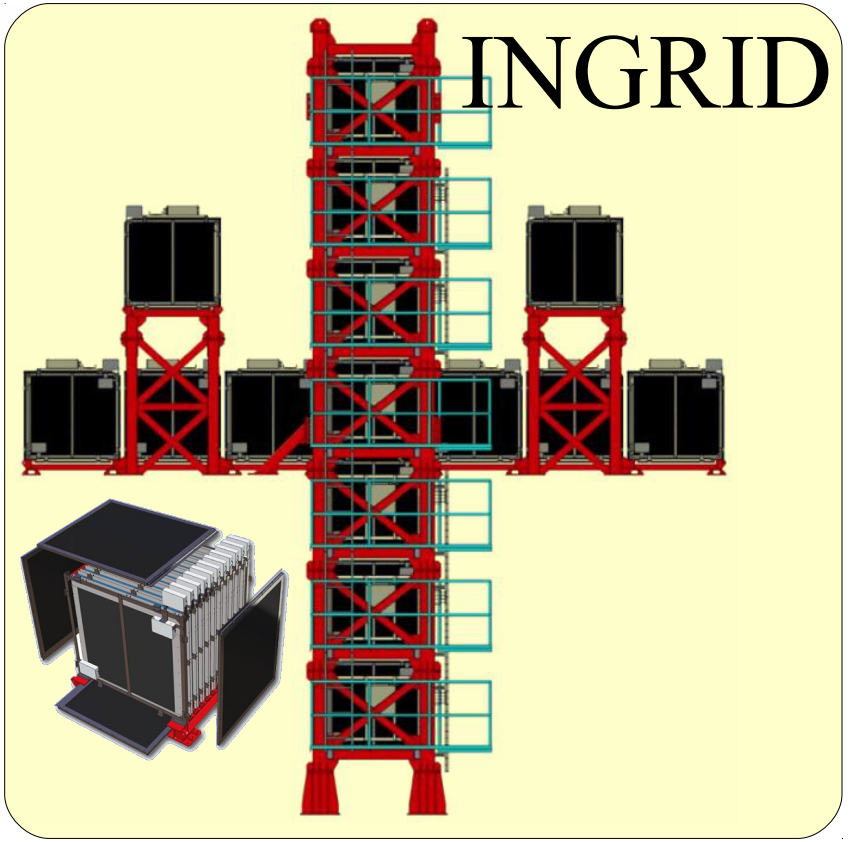


The ND280 Detectors

(**N**ear **D**etectors @ **280** Meters)

- On-Axis: INGRID
  - Neutrino Beam Monitor
    - Direction
    - Rate
  - Cross Sections

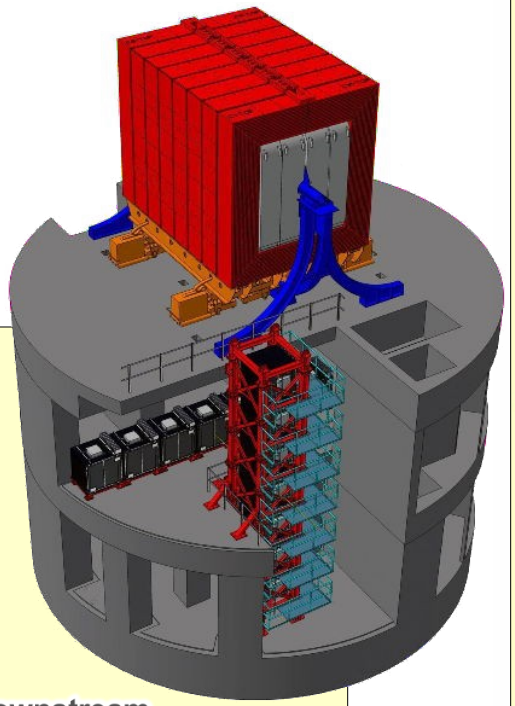


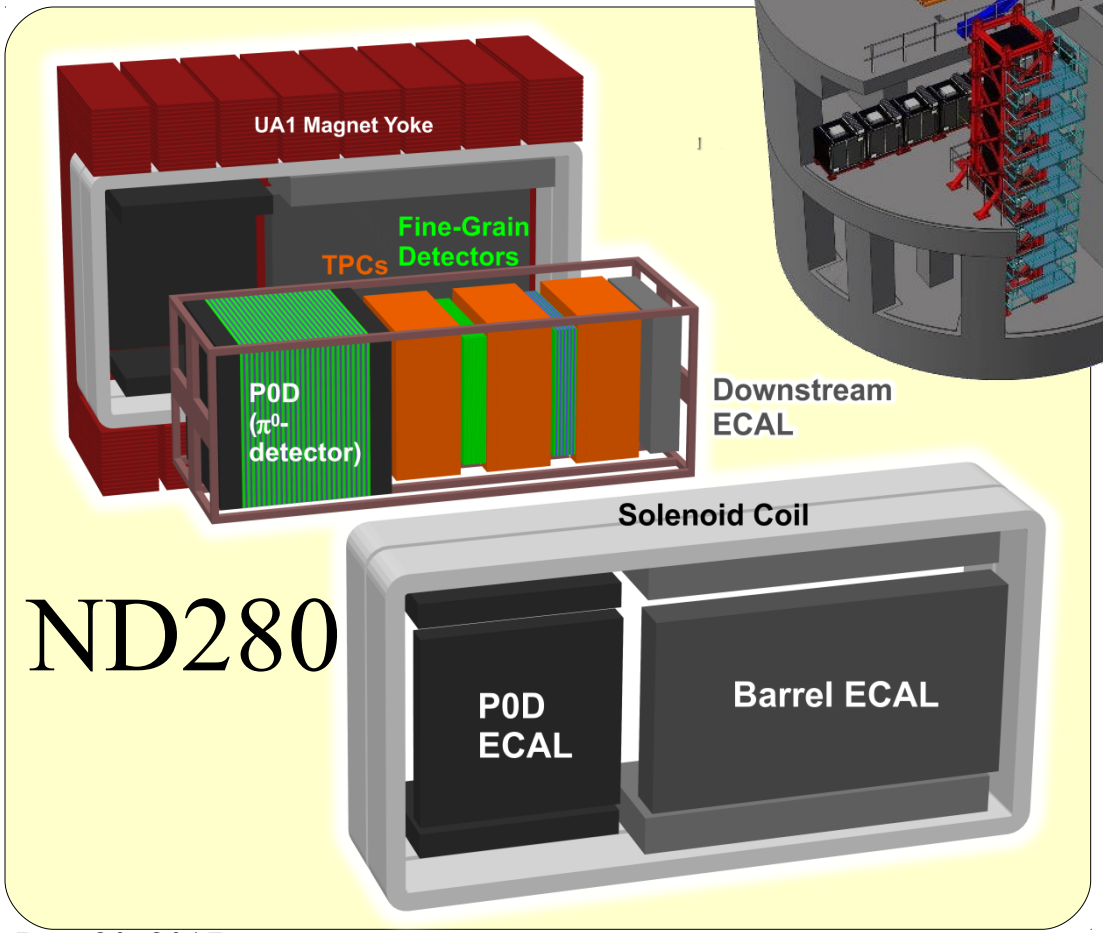


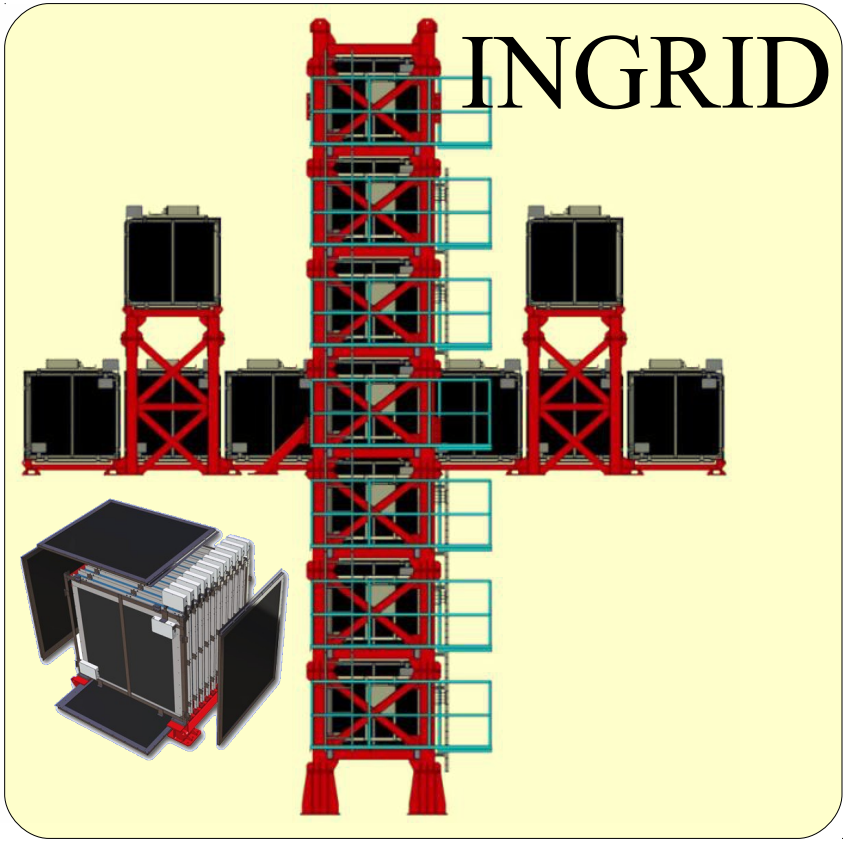
The ND280 Detectors

(Near Detectors @ 280 Meters)

- On-Axis: INGRID
  - Neutrino Beam Monitor
    - Direction
    - Rate
  - Cross Sections

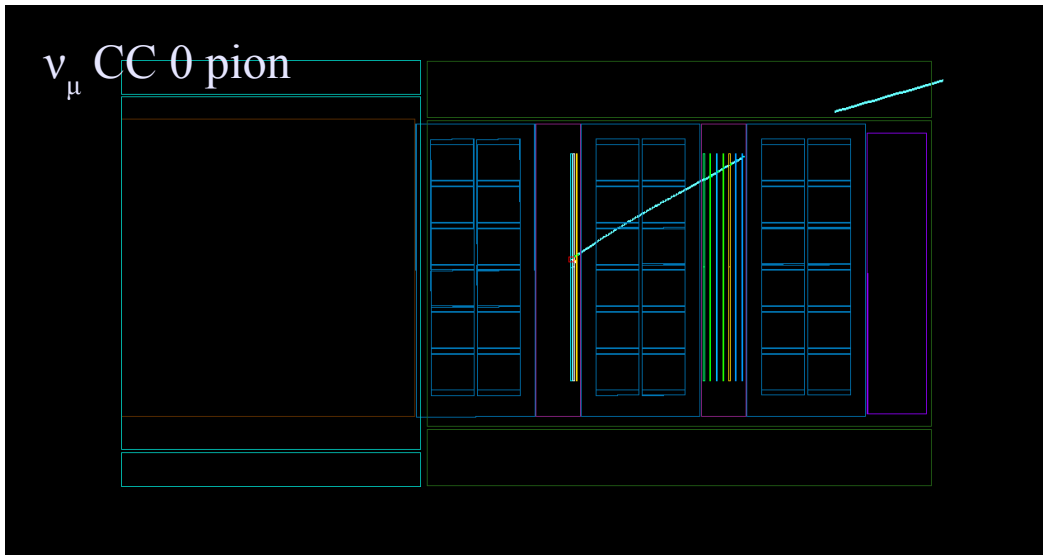


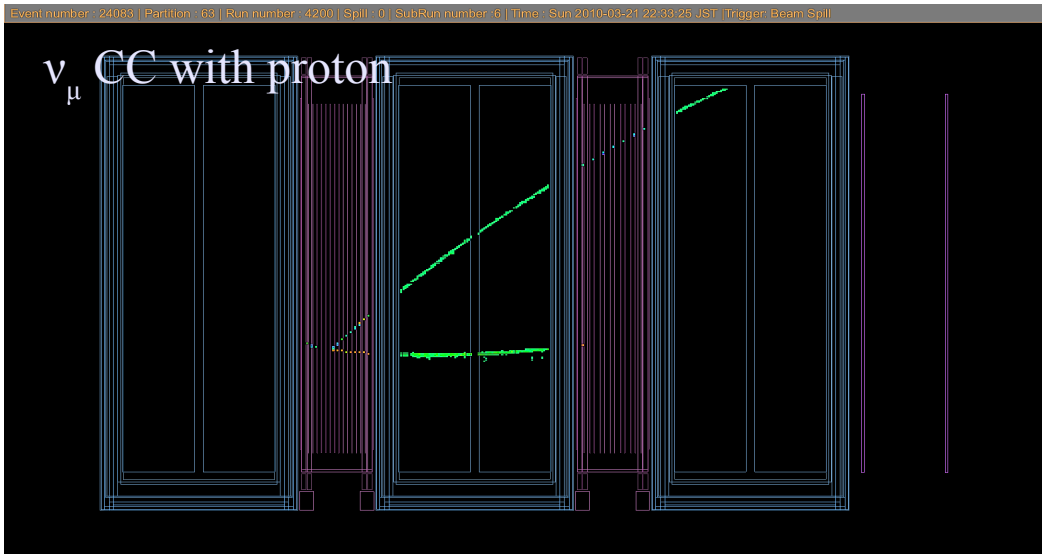


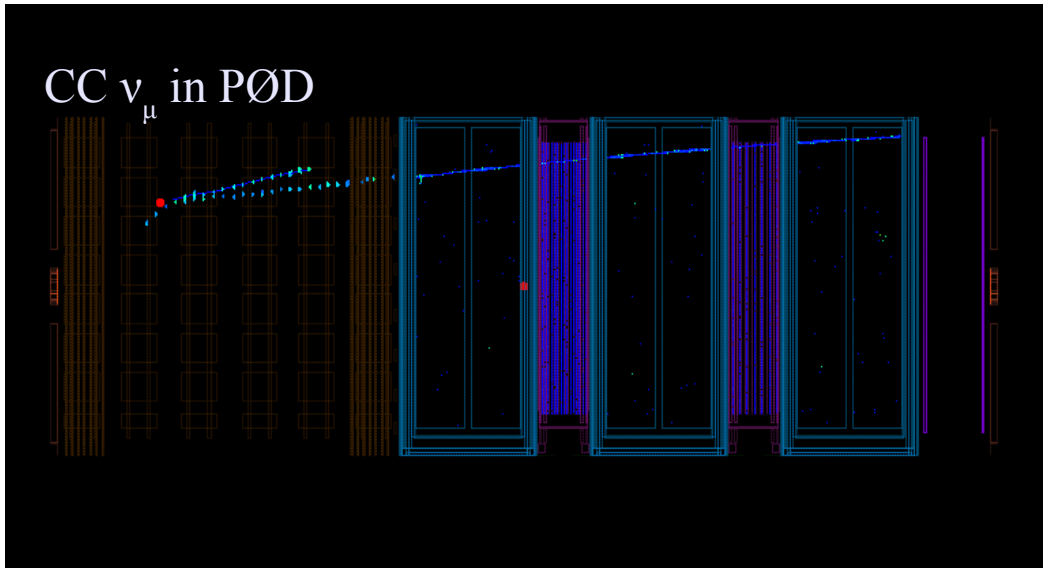


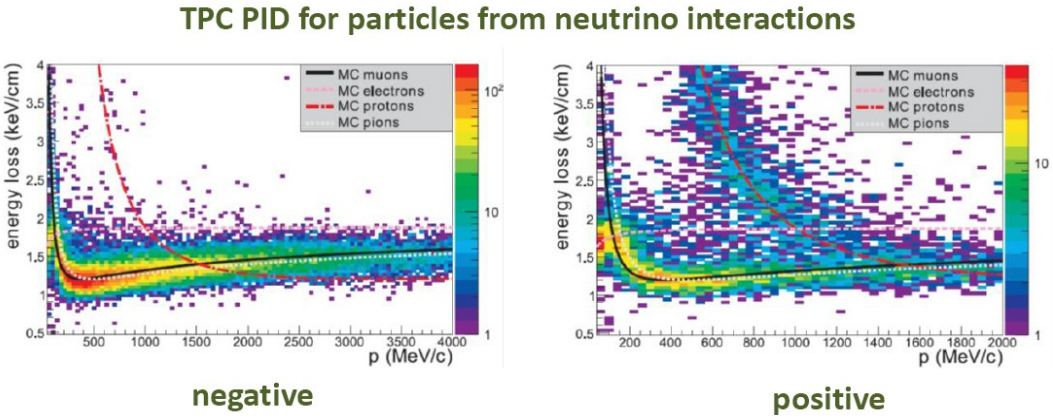
- Off-Axis: ND280 @ 2.5 deg
  - Off-axis flux and cross-sections
  - Target with water for stat. subtraction
  - In recycled UA1 magnet (@ 0.2 T)
    - Target+Particle Tracking
    - π^o detection
    - EM calorimetry
    - Side muon range detection

Typical ND280 Events



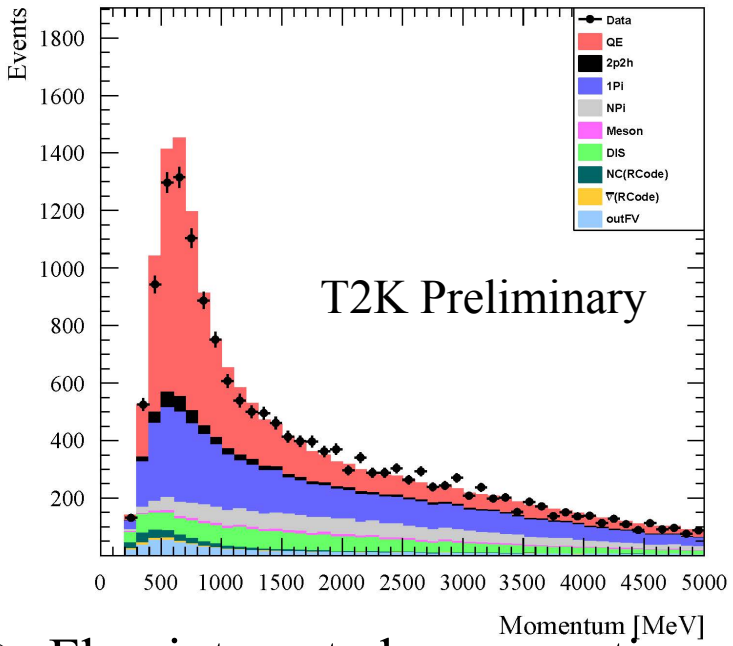




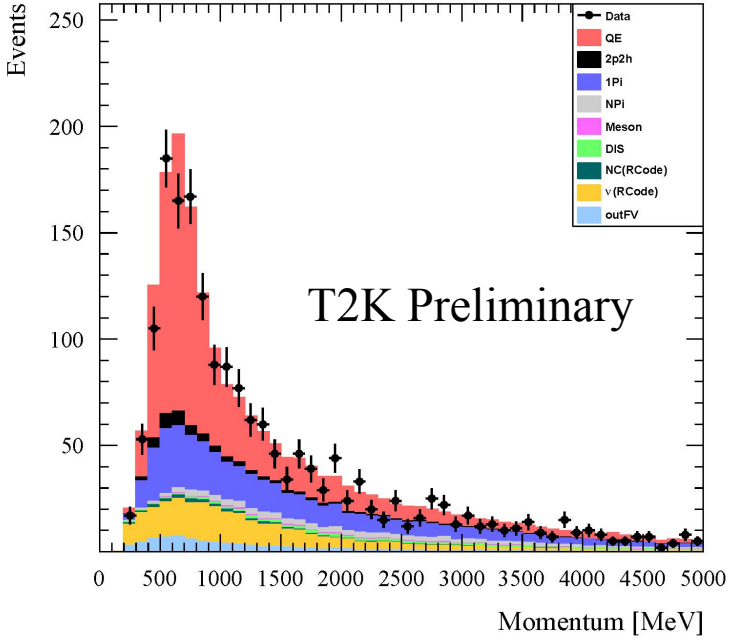


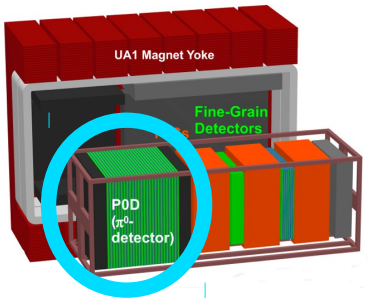
Inclusive CC $\sigma(\bar{\nu}_\mu)$ / $\sigma(\nu_\mu)$ on PØD

μ^- with forward horn current (ν_μ)



μ^+ with reverse horn current (anti-ν_μ)





The CC inclusive $\sigma(\bar{\nu}_\mu)$ and $\sigma(\nu_\mu)$ cross-sections are measured on the same target with the same detector configuration.

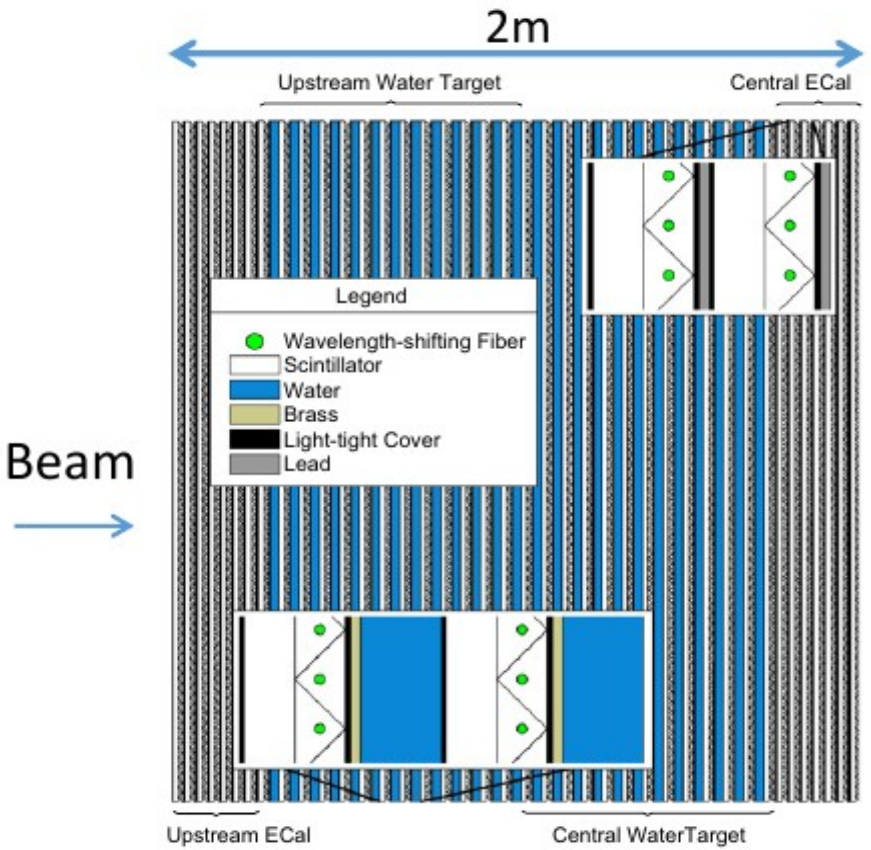
- Flux integrated cross sections on PØD
  - Carbon, Hydrogen, Oxygen, (Brass, &c)
  - Restricted to ND280 PØD+TPC phase space
    - $\theta_\mu < 32°$
    - $p_\mu > 500$ MeV/c

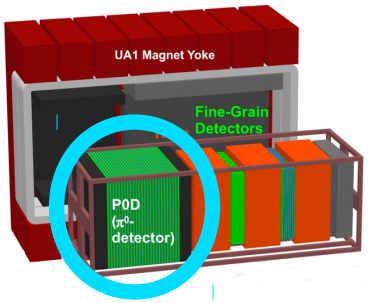
T2K Preliminary

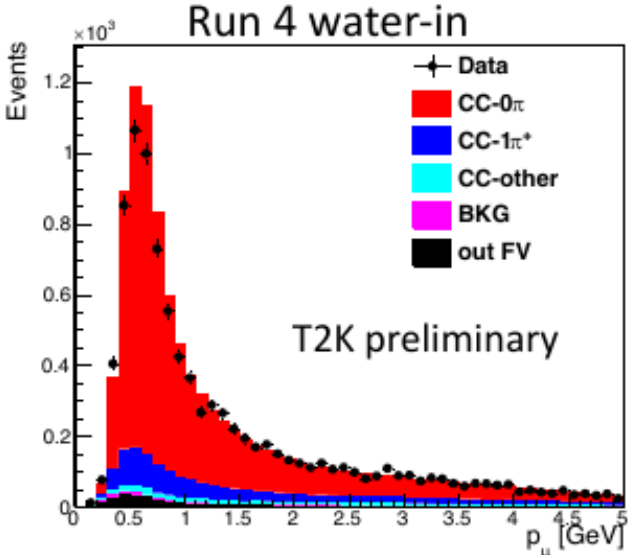
	data [$\times 10^{-39}$ cm^2/nucleon]		
$\bar{\nu}$ Cross section	0.8997	$\pm$ 0.0287 (stat.)	$\pm$ 0.0880 (syst.)
ν Cross section	2.4114	$\pm$ 0.0217 (stat.)	$\pm$ 0.2310 (syst.)
$\sigma(\nu) - \sigma(\bar{\nu})$	1.5117	$\pm$ 0.0360 (stat.)	$\pm$ 0.1524 (syst.)
$\sigma(\nu) + \sigma(\bar{\nu})$	3.3110	$\pm$ 0.0360 (stat.)	$\pm$ 0.3182 (syst.)
	data		
$\sigma(\bar{\nu})/\sigma(\nu)$	0.3731	$\pm$ 0.0124 (stat.)	$\pm$ 0.0152 (syst.)
$(\sigma(\nu) - \sigma(\bar{\nu}))/(\sigma(\nu) + \sigma(\bar{\nu}))$	0.4566	$\pm$ 0.0120 (stat.)	$\pm$ 0.0171 (syst.)

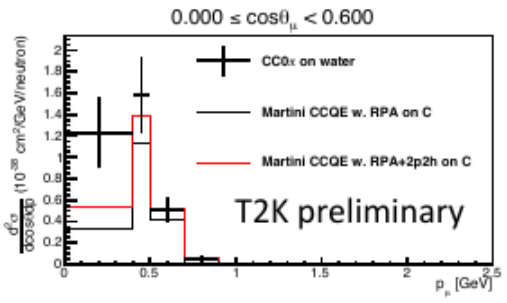
arxiv:1706.04257

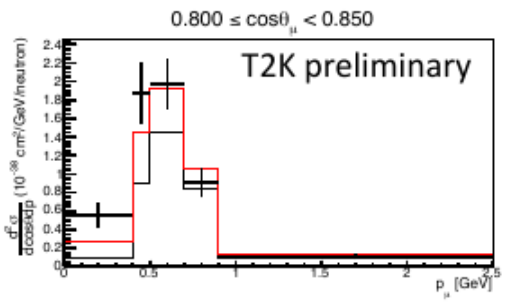
Inclusive CC ν_μ on Water

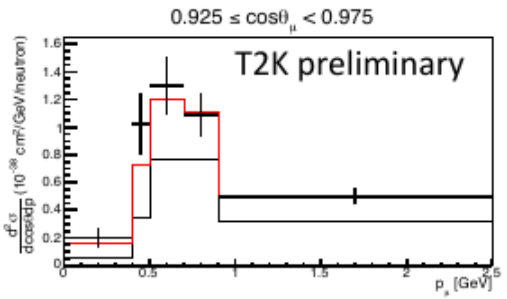


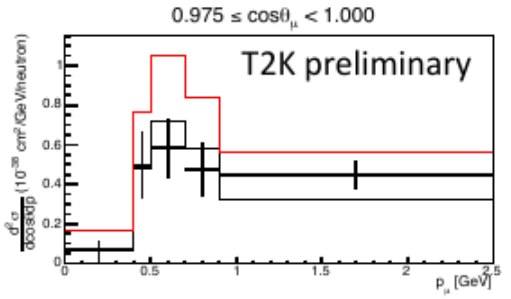










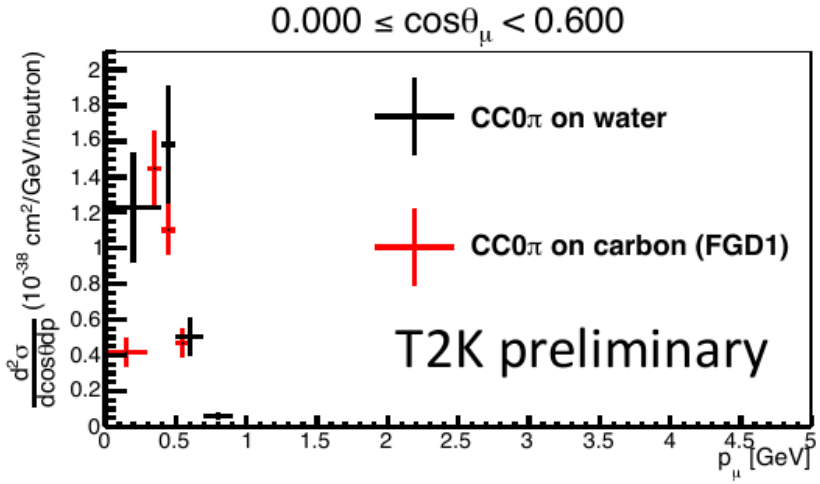


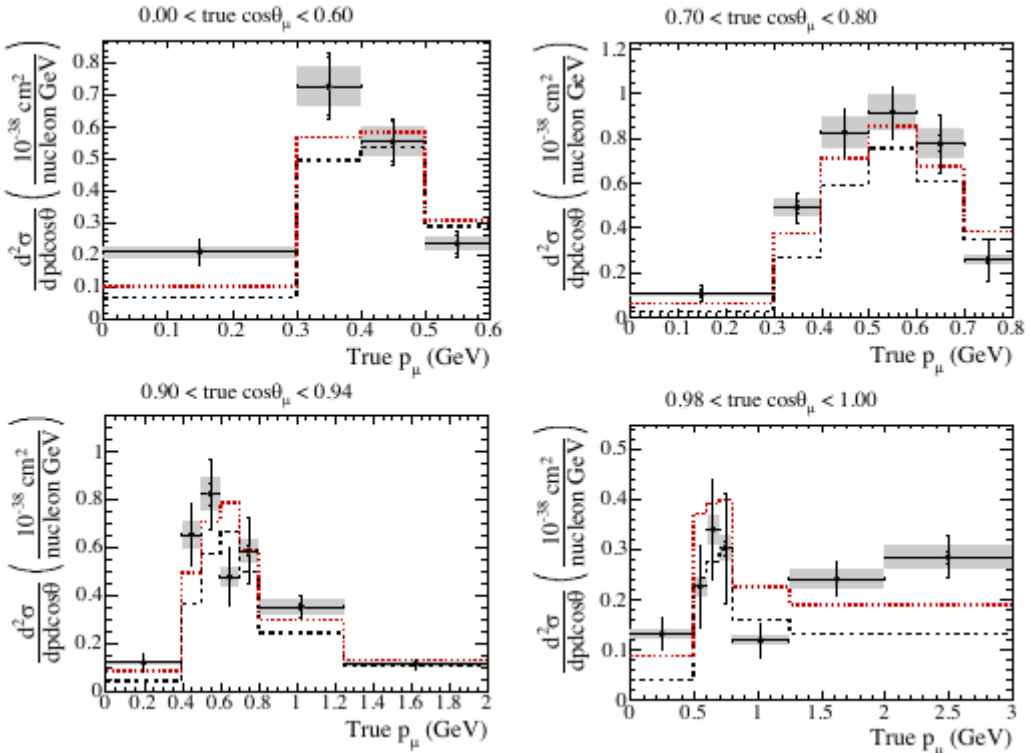
- Measure p_μ and $\cos(\theta_\mu)$
- Bayesian unfolding to remove detector response
  - Unfold water-in and water-out separately
- Statistical subtraction to get cross section on water.

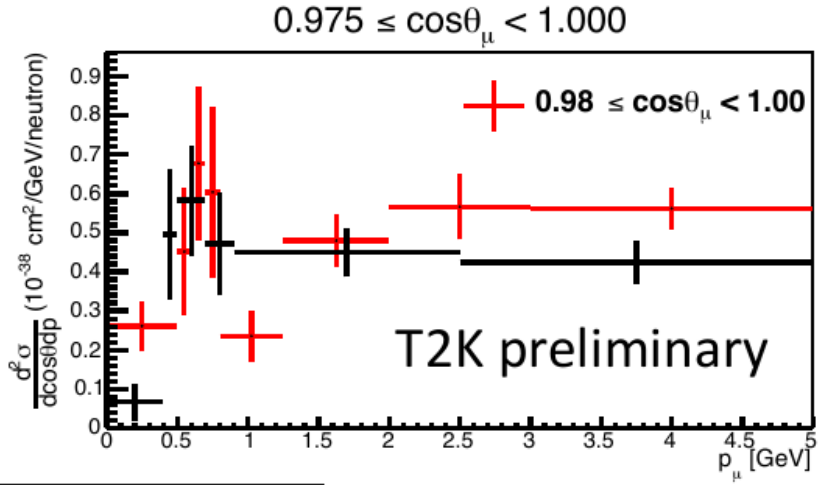
arxiv:1611.03536

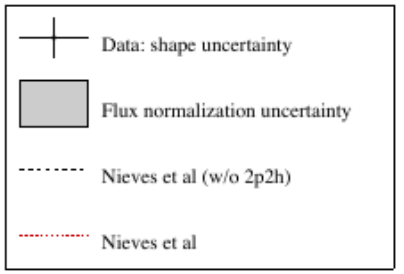
Inclusive CC ν_μ on Hydrocarbon

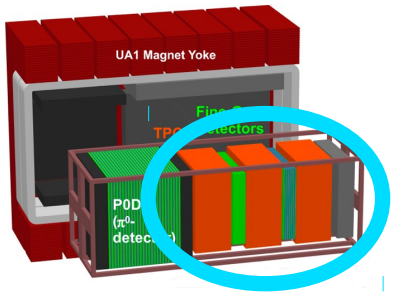
- Understanding the water vs carbon cross section difference is important to reducing systematics in oscillation analysis





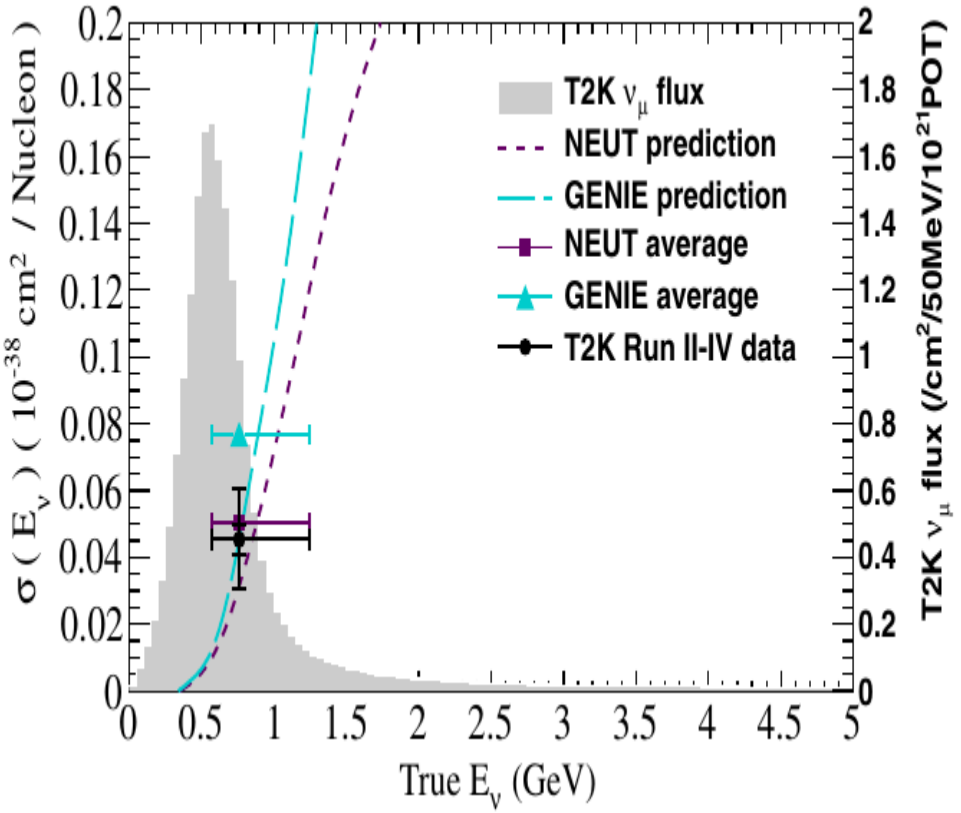


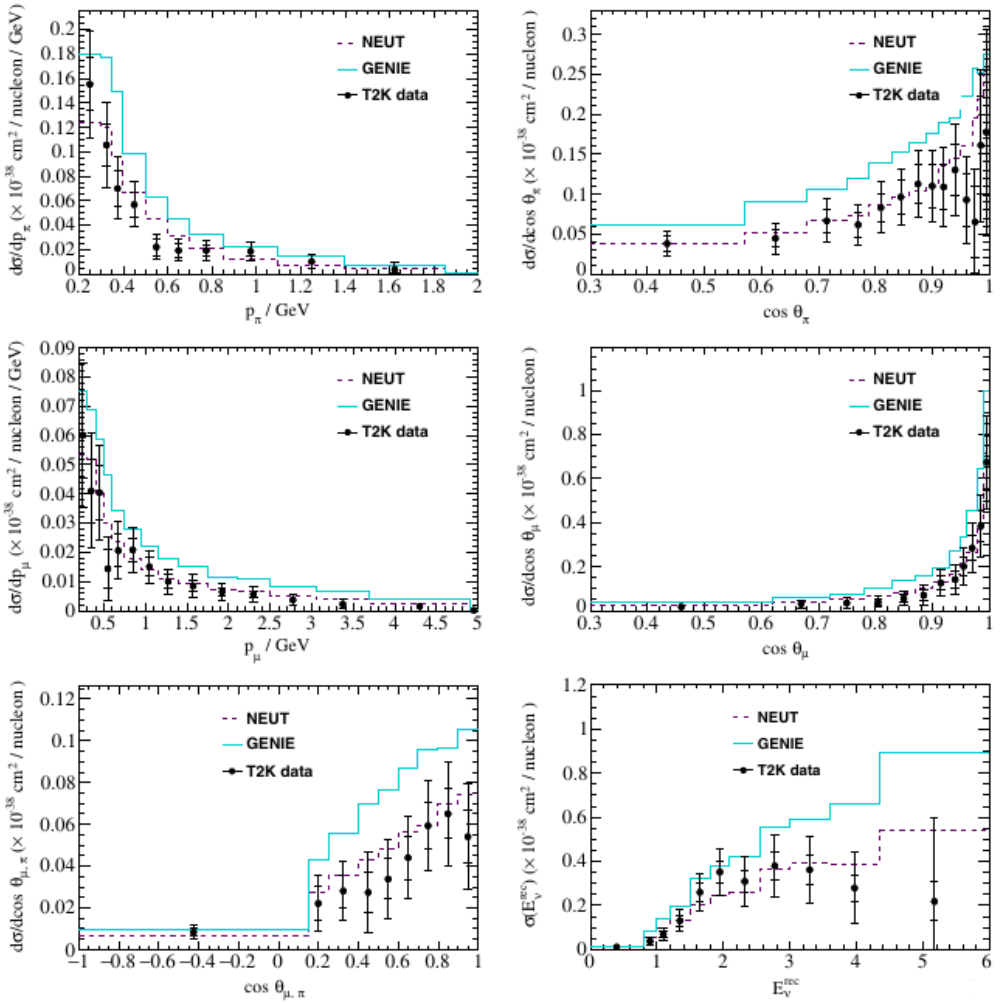




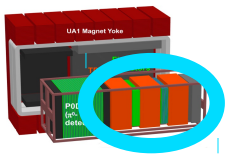
CC ν_μ Single π^+ Production on Water

- First differential cross section for CC π^+ on water
  - Statistical subtraction of
    - FGD2 (water+scintillator)
    - FGD1 (scintillator)
- Bayesian unfolding with background subtraction





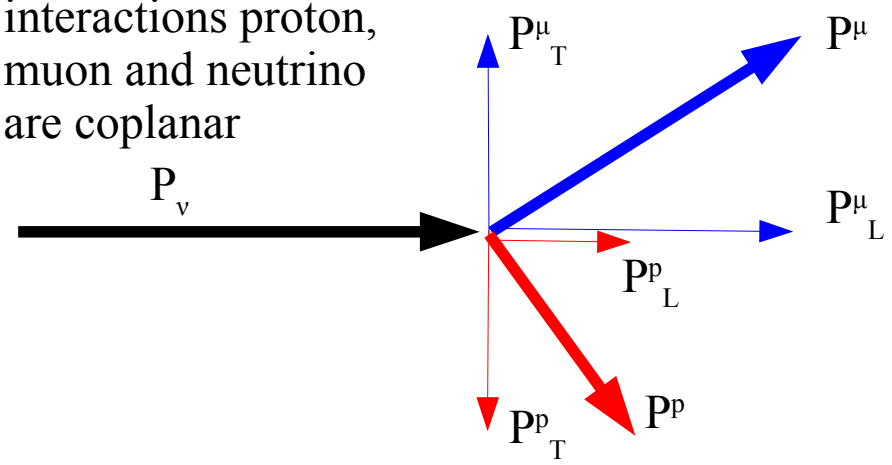
PRD 95, 012010

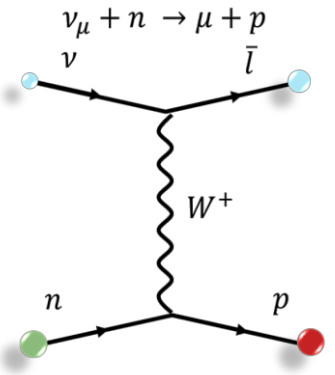


Transverse Momentum Imbalance
CC 0π + (>0) p

Without nuclear effects: $-P_T^{\mu} = P_T^{p}$

Without nuclear interactions proton, muon and neutrino are coplanar

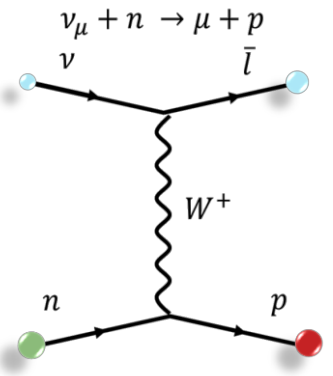




No nuclear effects in the bare ineraction.

Transverse Momentum Imbalance
CC 0π + (>0) p

Without nuclear effects: $-P_T^{\mu} = P_T^{p}$



No nuclear effects
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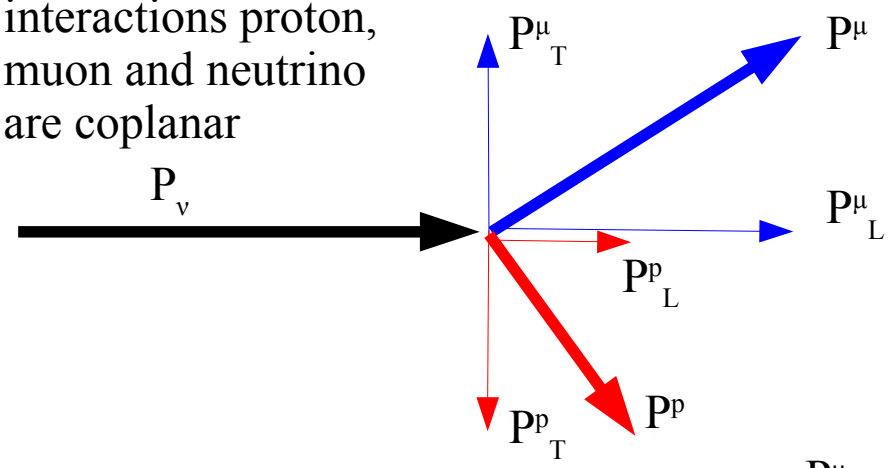
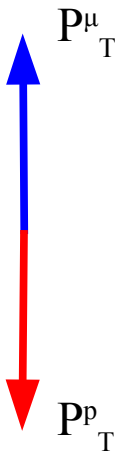
Without nuclear interactions proton, muon and neutrino are coplanar

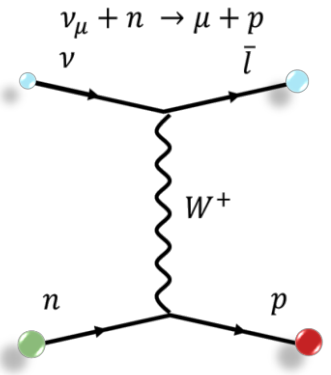


Looking along the neutrino direction, the transverse momentum is balanced



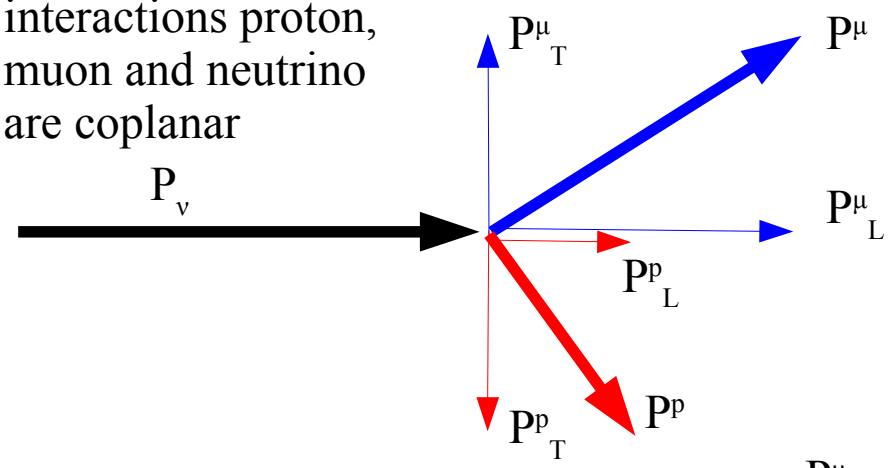
Transverse Momentum Imbalance
CC 0π + (>0) p

Without nuclear effects: $-P_T^{\mu} = P_T^{p}$



No nuclear effects
in the bare ineraction.

Without nuclear interactions proton, muon and neutrino are coplanar



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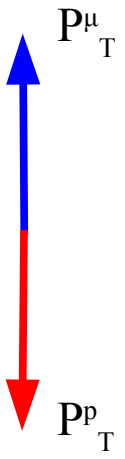
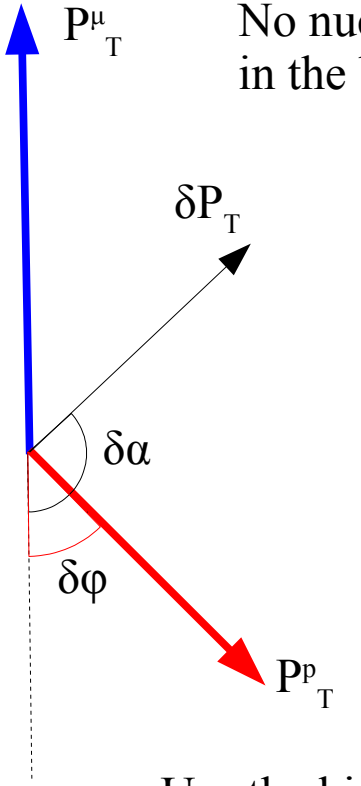




Nuclear interactions will modify the proton direction

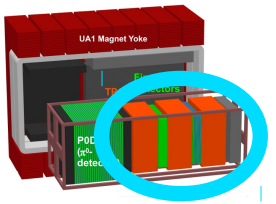
Use asymmetry to probe effect of nucleus

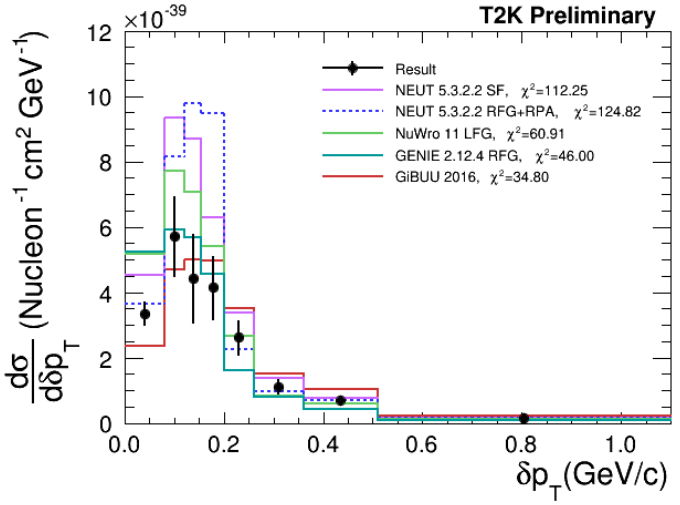
PRC 94, 015503

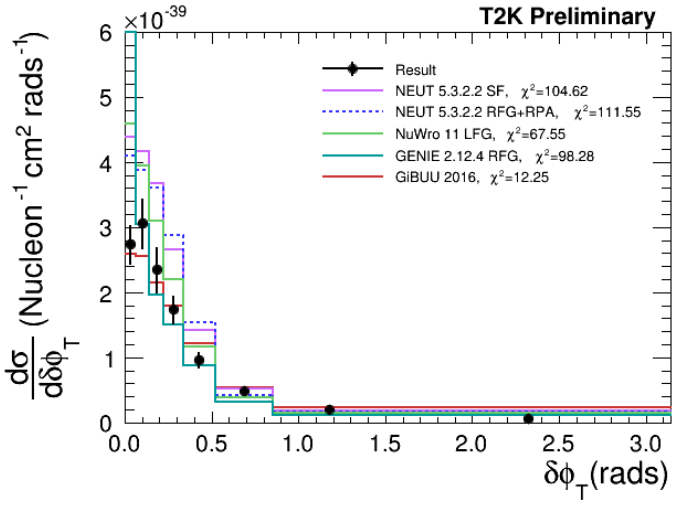
Use the highest momentum proton

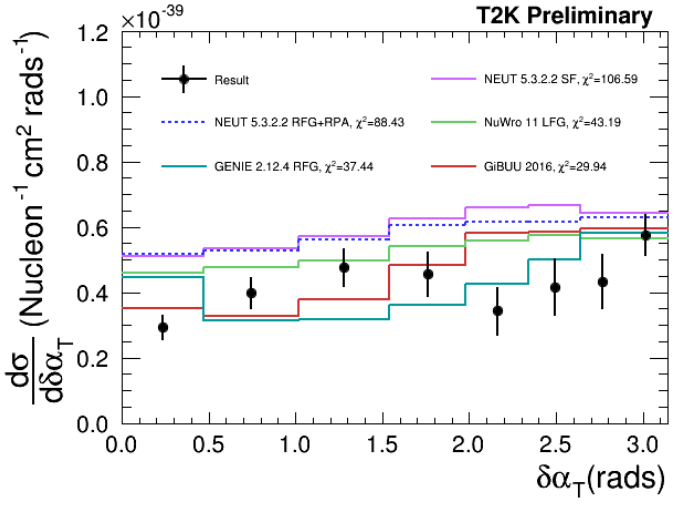
Flux Integrated CC 0π + (>0) p

- Measure the fiducial flux-integrated CC 0π + (>0) p cross section in bins of transverse momentum imbalance variables (δP, δφ, δα)
- Restrict cross section to the ND280 Tracker acceptance
  - $p_\mu > 250$ MeV/c
  - $\cos(\theta_\mu) > -0.6$
  - 450 MeV/c $< p_p <$ 1 GeV/c
  - $\cos(\theta_p) > 0.4$

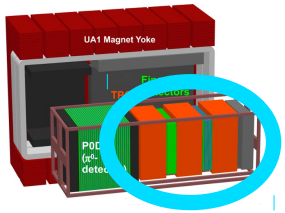


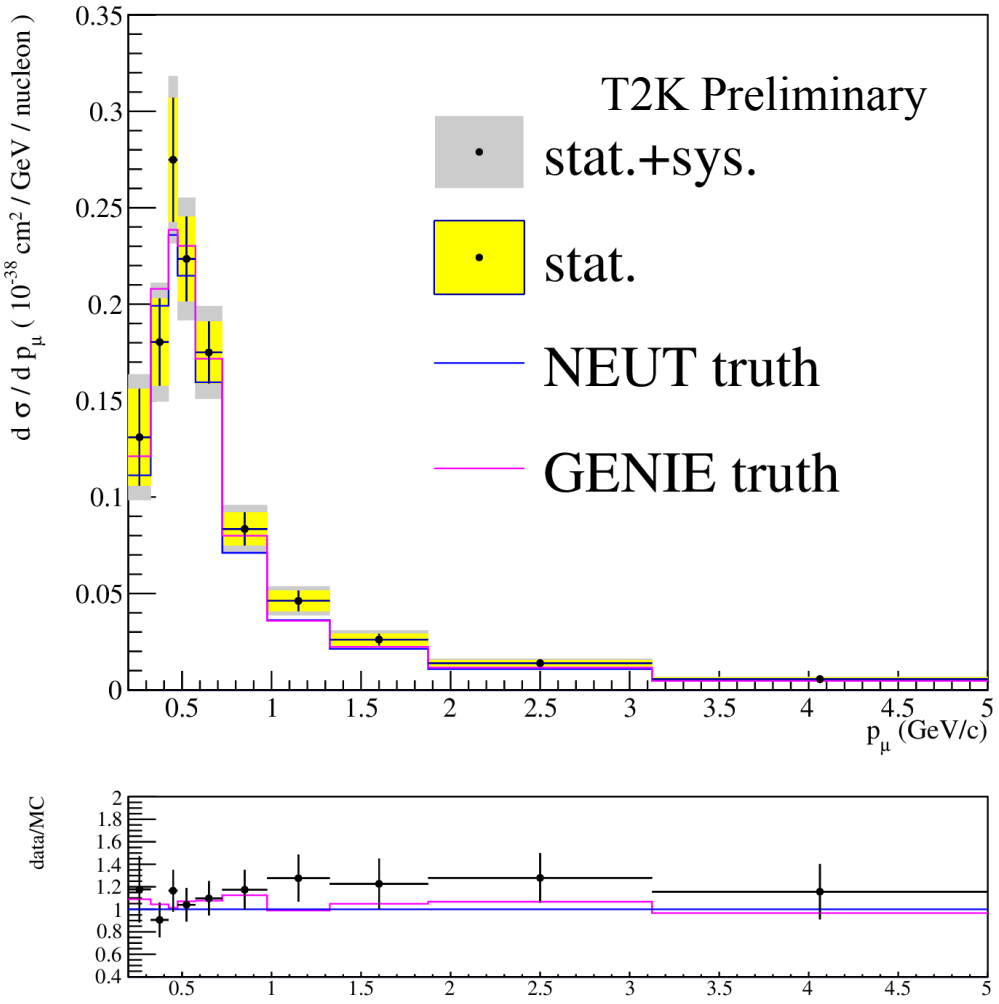




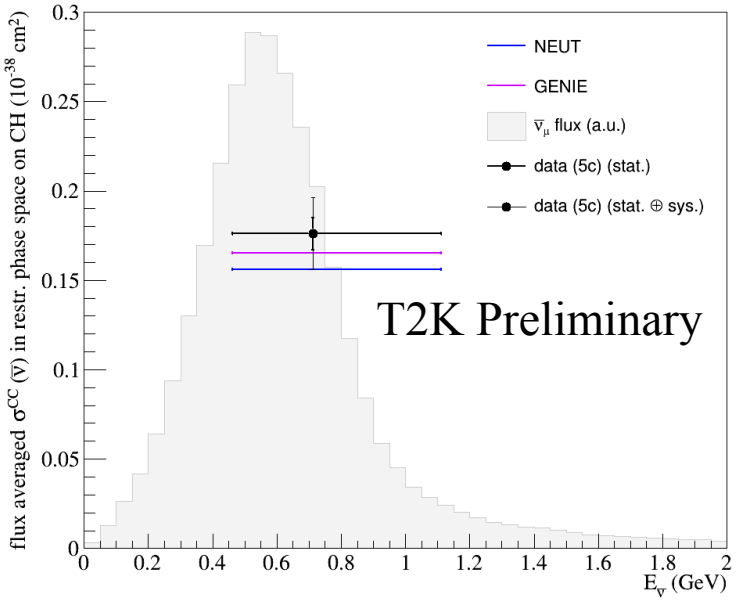


Flux Averaged CC Inclusive anti-ν_μ on Scintillator Targets





- Select highest momentum FGD+TPC track consistent with muon
- Apply Quality, PID, and Veto cuts
- Control sample used to determine proton contamination
  - Hard to distinguish in 1-2 GeV/c region



T2K-TN-249

Conclusions and Summary

- In addition to being the near detector complex for the T2K oscillation analysis, the T2K near detectors are producing new and important cross section measurements.
  - Recent publications include differential and double differential cross sections on water and carbon
  - Several results being prepared for publication
- Anti neutrino cross section measurements are starting to emerge
- Some results not discussed
  - CC quasi-elastic on iron (PRD 93 072002)
  - CC 0 π on carbon (PRD 93 112012)
  - Search for CC coherent π^+ production (PRL 117:192501)
- Expect many more cross section results from T2K in the (near) future.

Stony Brook University

T2K

The T2K Collaboration
Thank You

The T2K Collaboration

~ 500 members, 63 Institutes, 11 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
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Kobe U.
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Miyagi U. Edu.
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U. Warsaw
Warsaw U. T.
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Russia
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IFIC, Valencia
U. Autonoma Madrid

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Royal Holloway U.L.
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STFC/RAL
U. Liverpool
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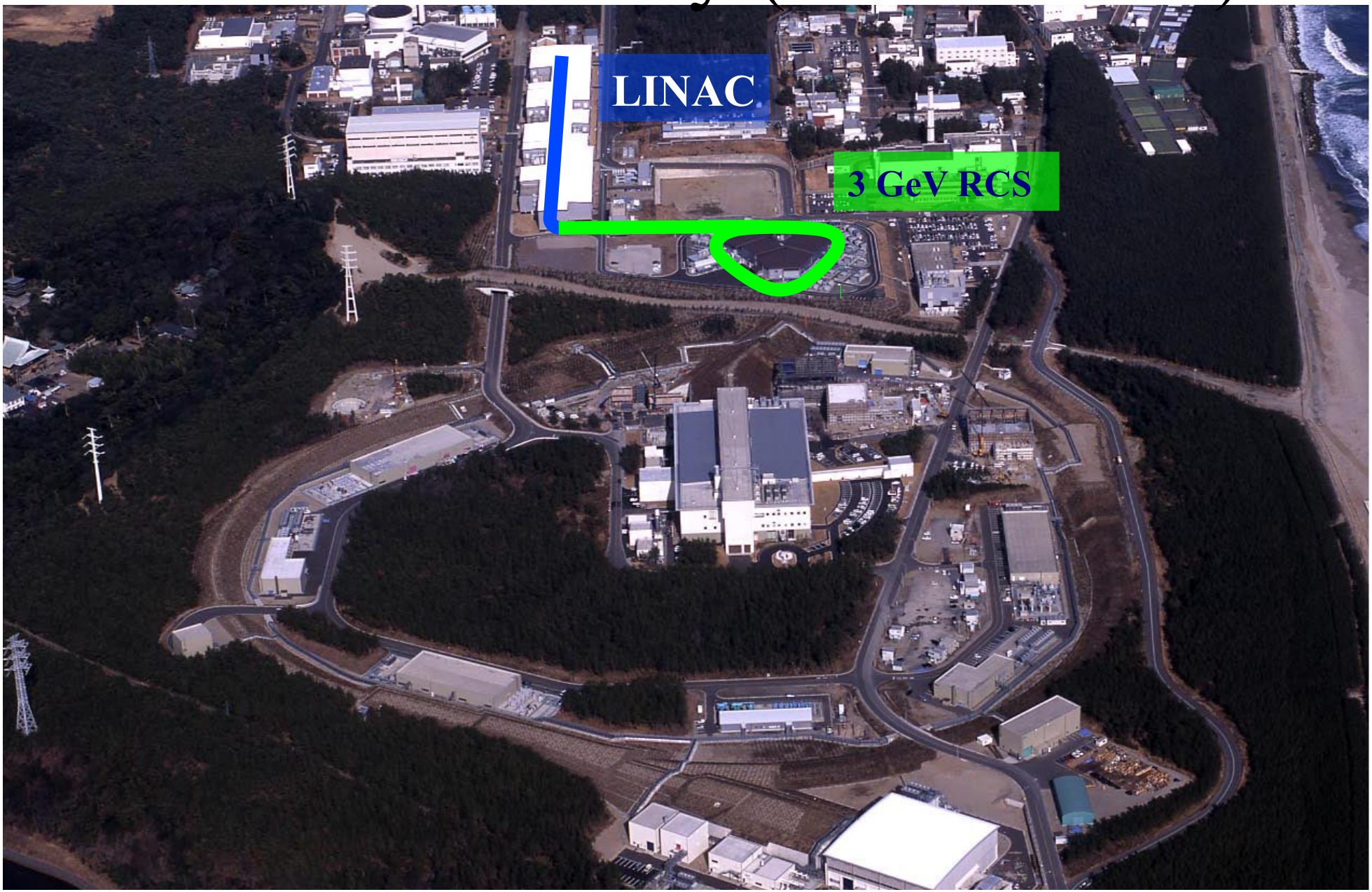
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Backup Slides

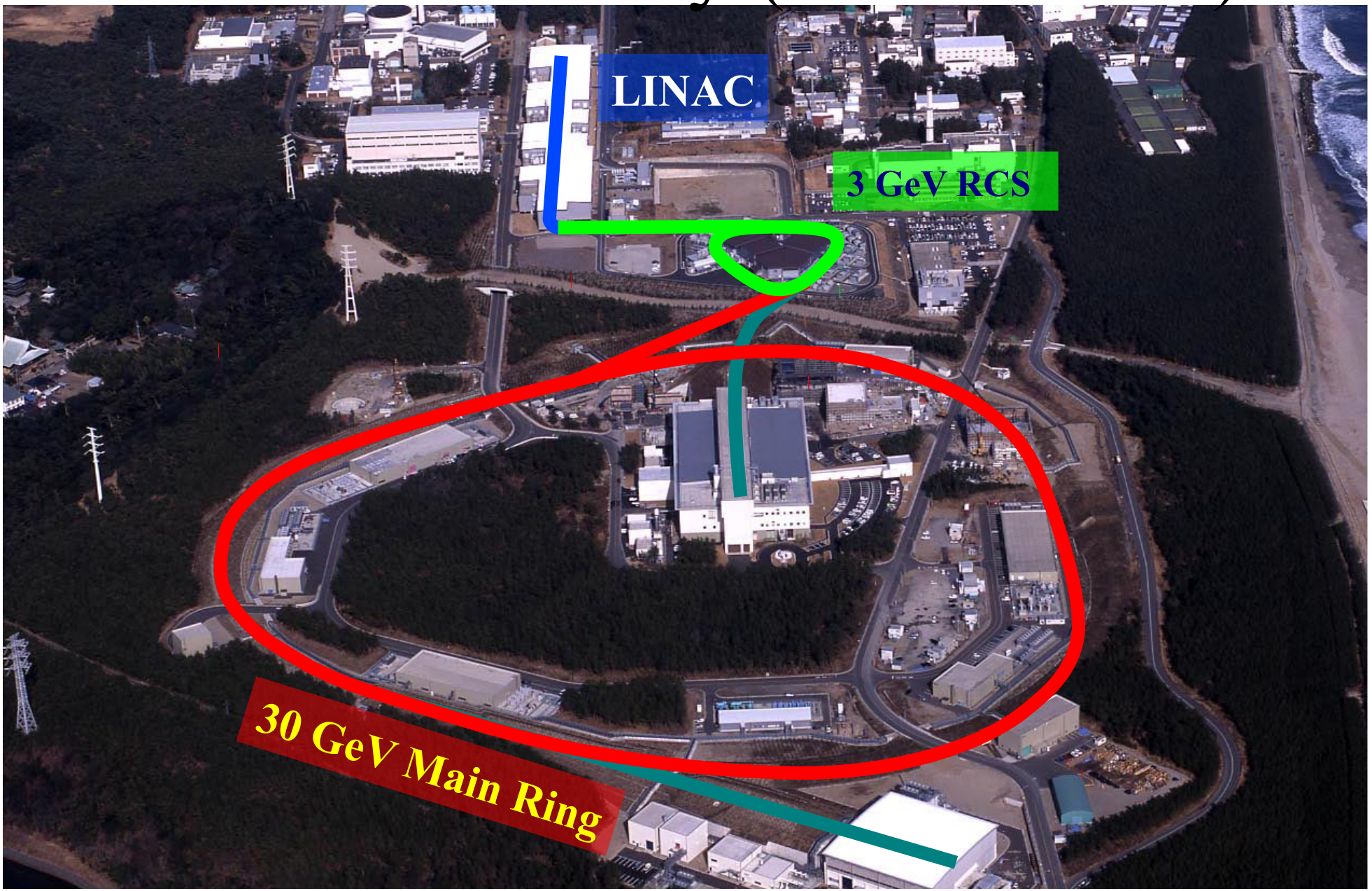
J-PARC facility (KEK/JAEA)

J-PARC facility (KEK/JAEA)

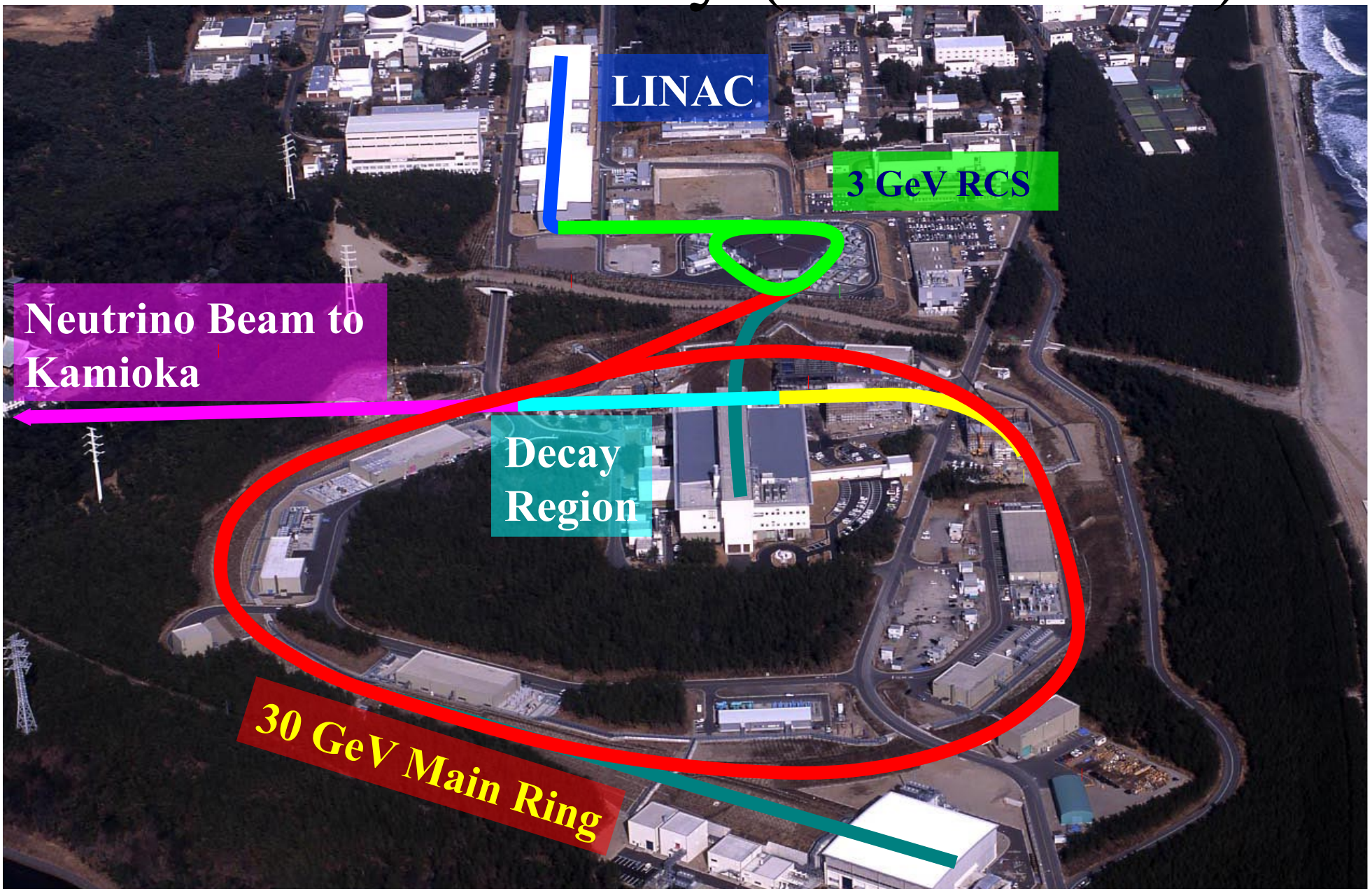
J-PARC facility (KEK/JAEA)



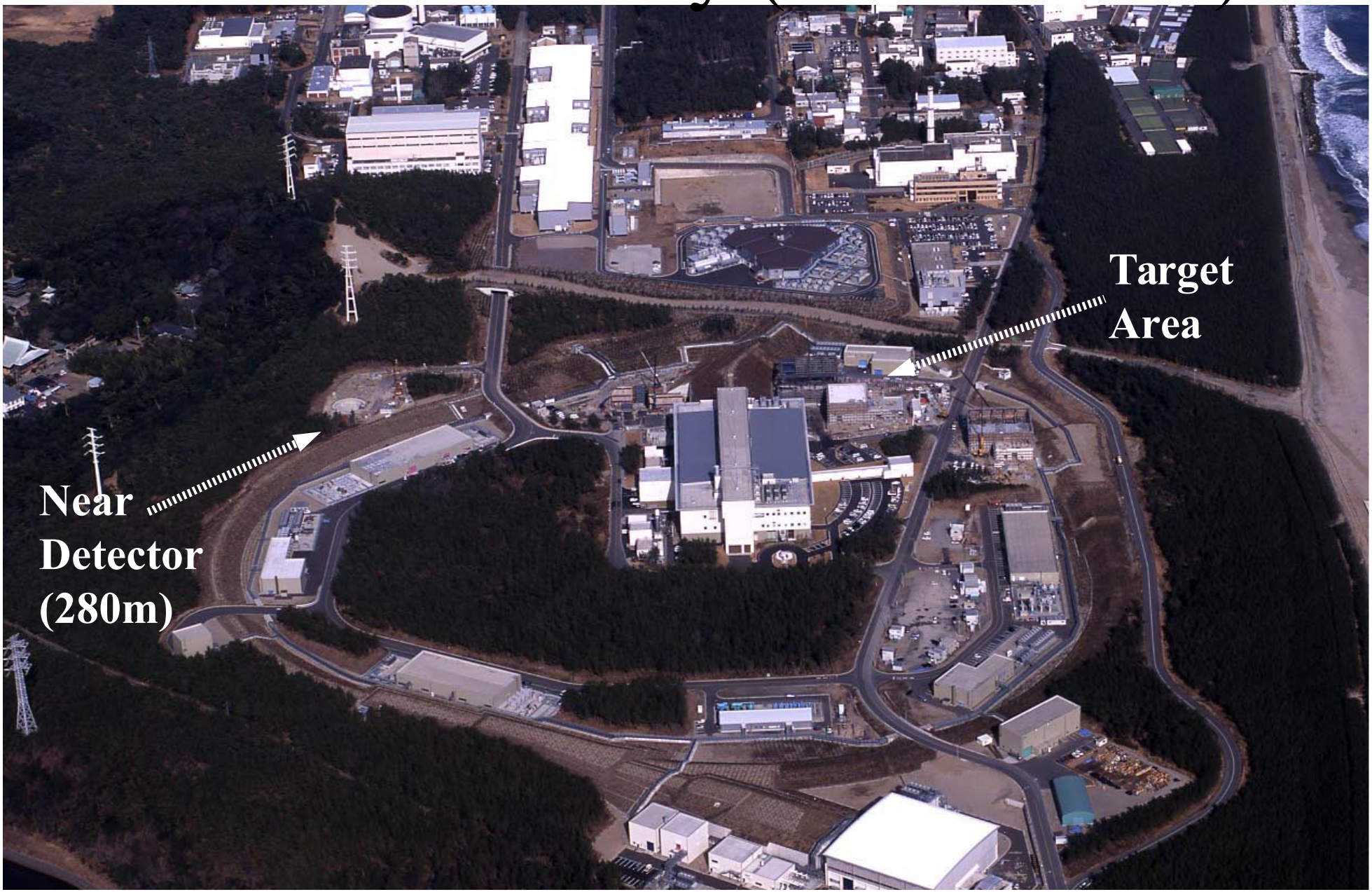
J-PARC facility (KEK/JAEA)



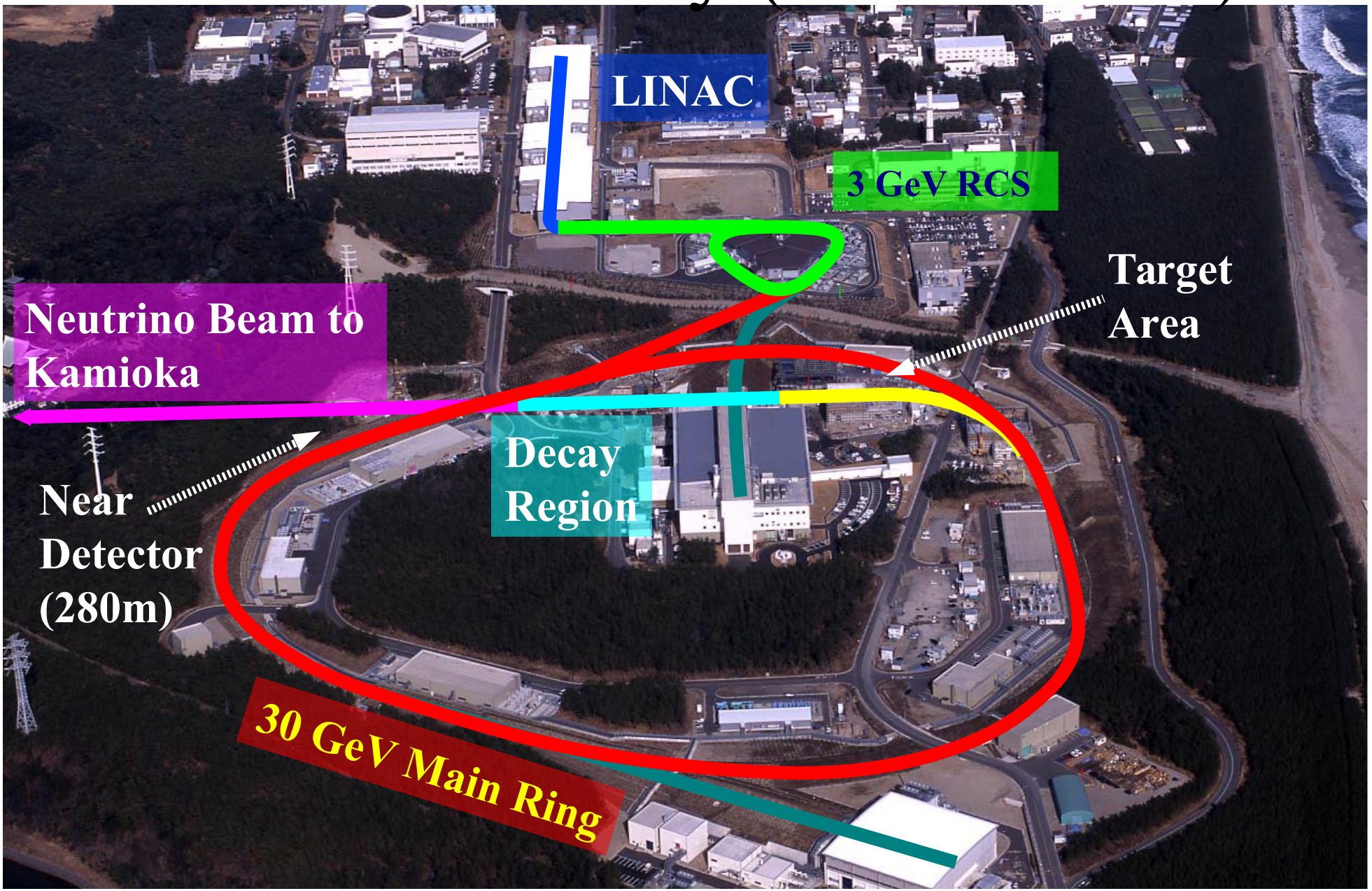
J-PARC facility (KEK/JAEA)



J-PARC facility (KEK/JAEA)



J-PARC facility (KEK/JAEA)



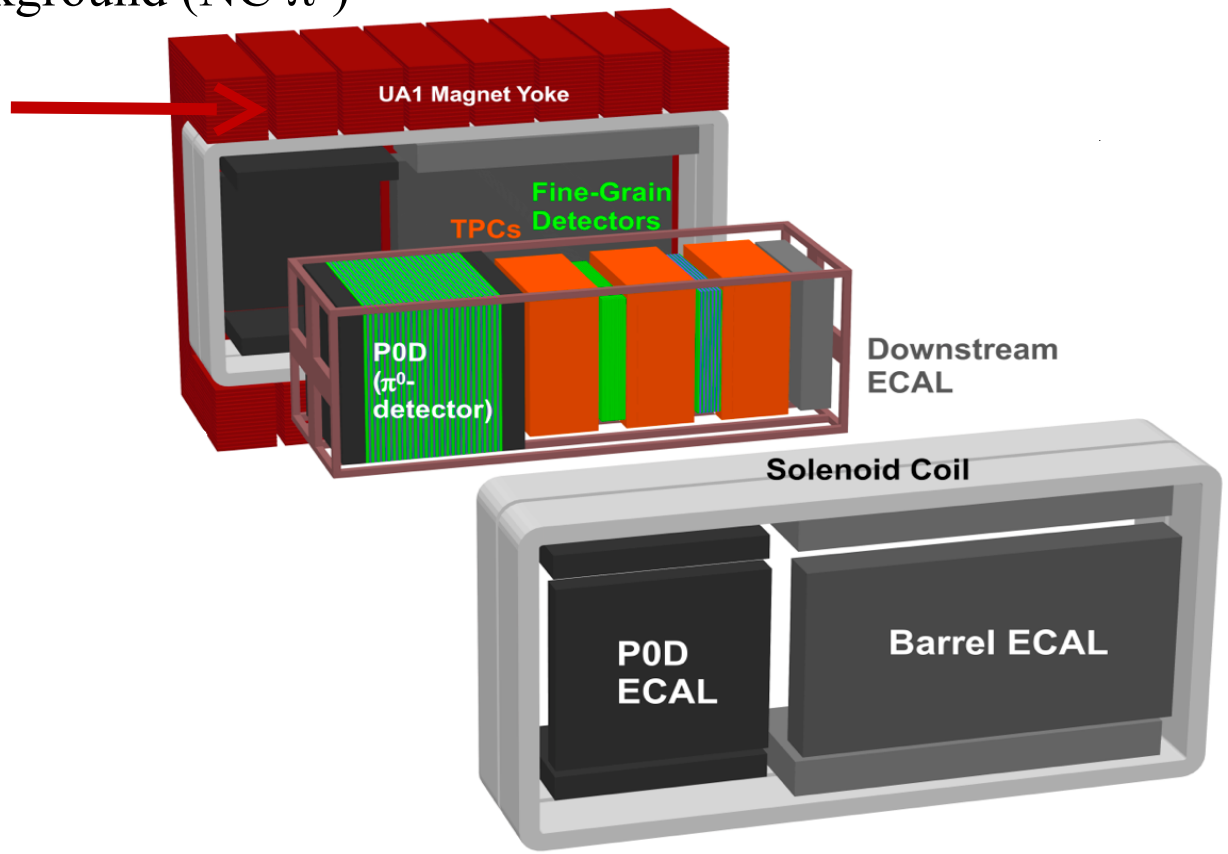
ND280 Off-axis Detector

Designed for measurement of

- Off-axis spectrum using CC ν_μ interactions
- Beam ν_e contamination
- Super-K background (NC π^0)

Magnet

- **0.2 T**



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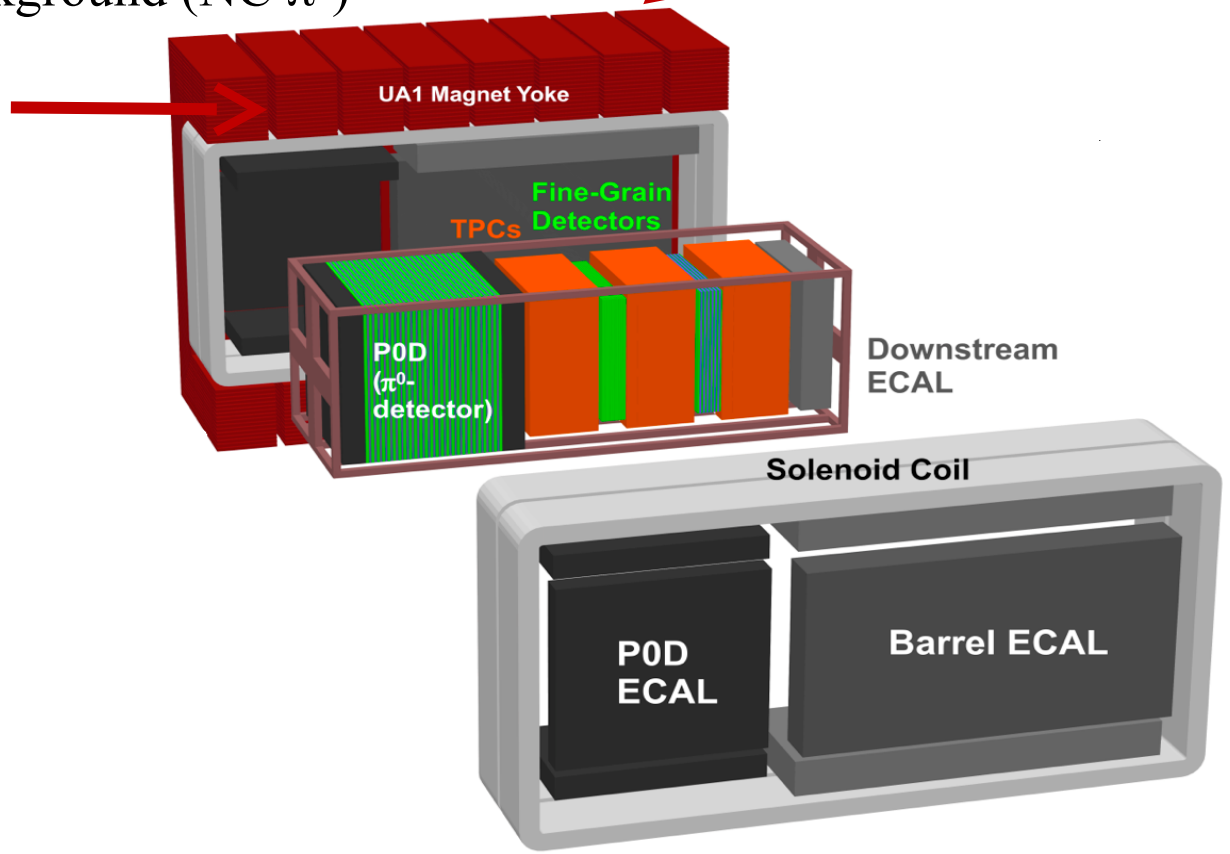
- **0.2 T**

SMRD (Side Muon Range Detector)

- Scintillator planes in magnet yoke
- Detect muons from inner detector
- Momentum measurement



ND280 Off-axis Detector

Designed for measurement of

- Off-axis spectrum using CC ν_μ interactions
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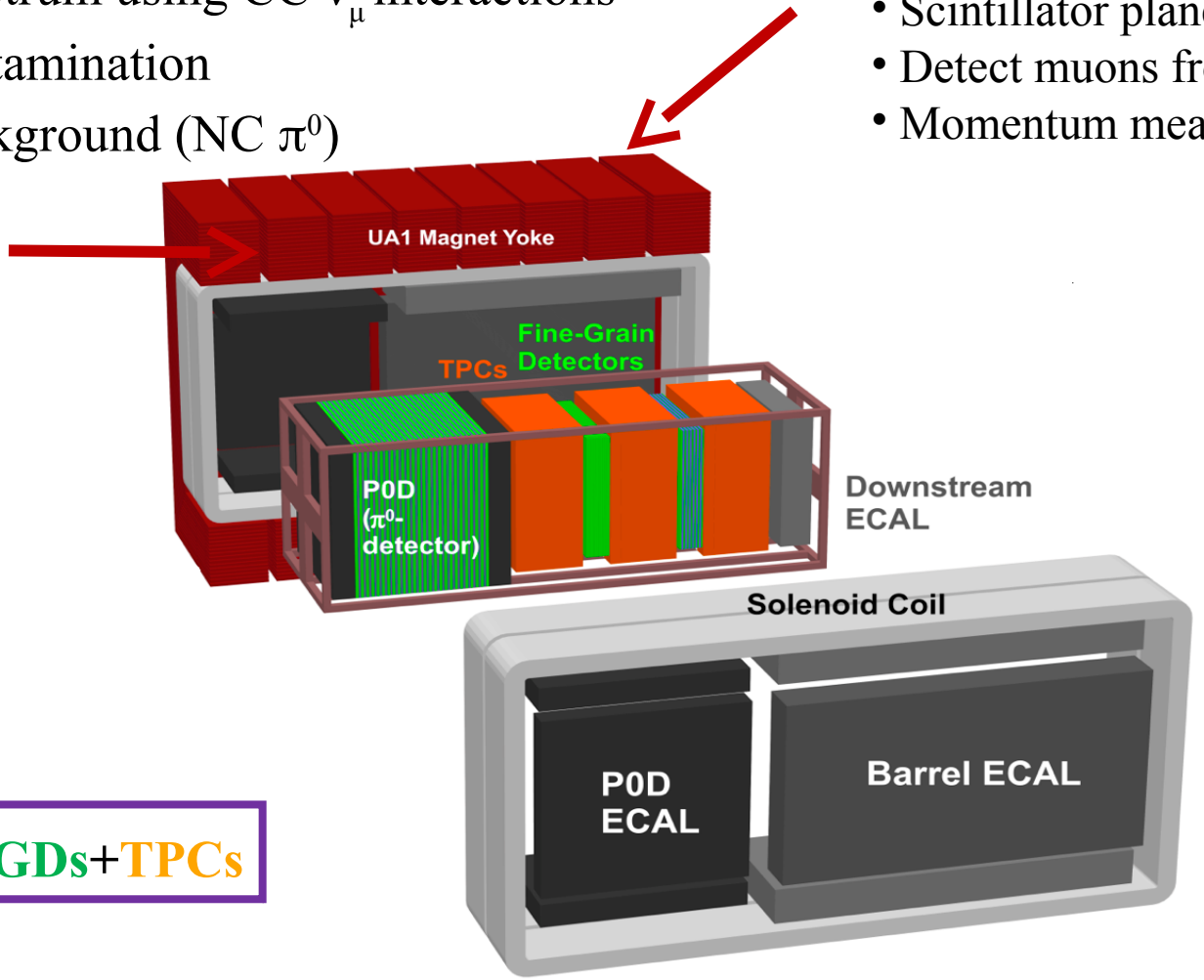


Tracker: FGDs+TPCs

ND280 Off-axis Detector

Designed for measurement of

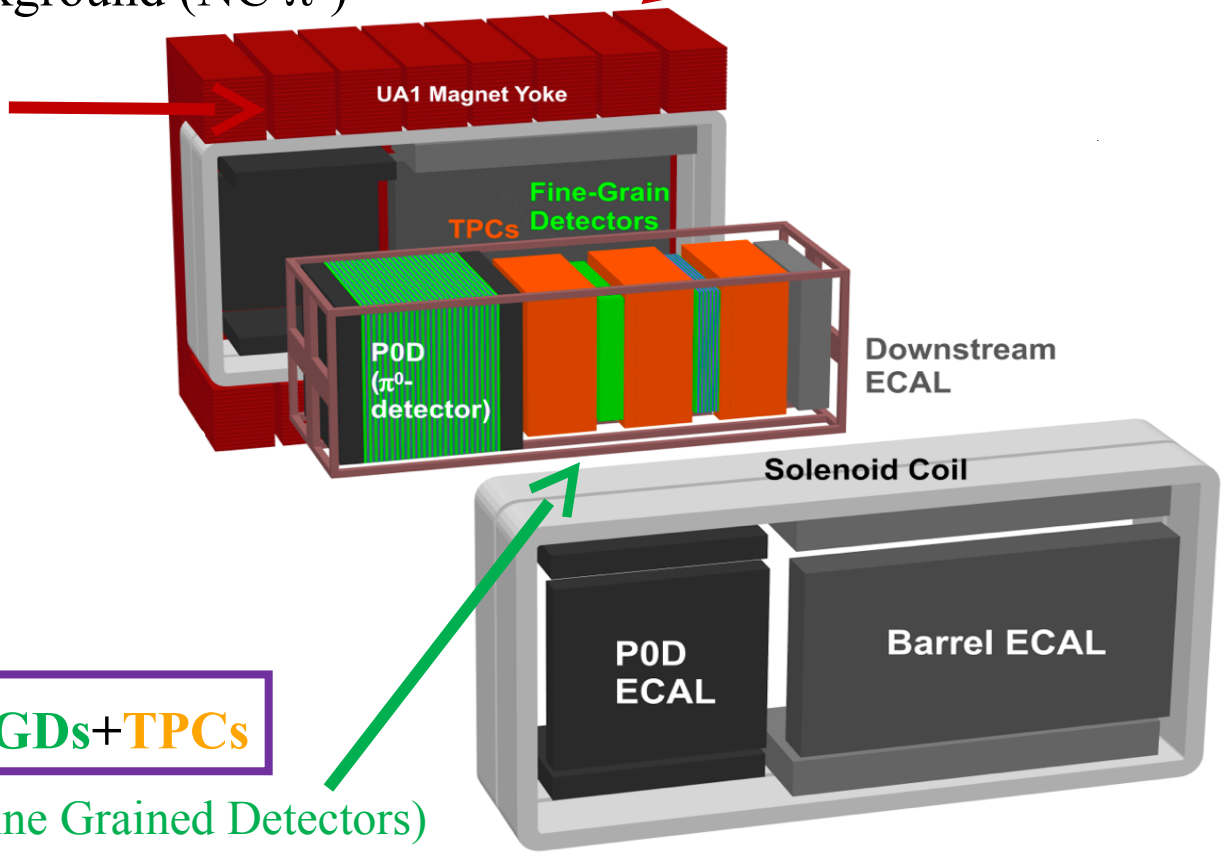
- Off-axis spectrum using CC ν_μ interactions
- Beam ν_e contamination
- Super-K background (NC π^0)

Magnet

- **0.2 T**

SMRD (Side Muon Range Detector)

- Scintillator planes in magnet yoke
- Detect muons from inner detector
- Momentum measurement



Tracker: FGDs+TPCs

FGDs (x2) (Fine Grained Detectors)

- Provide full active target mass
- FGD1: Scintillator planes ~ 1 ton
  FGD2: Scinti. & water planes ~ 0.5 & 0.5 ton

ND280 Off-axis Detector

Designed for measurement of

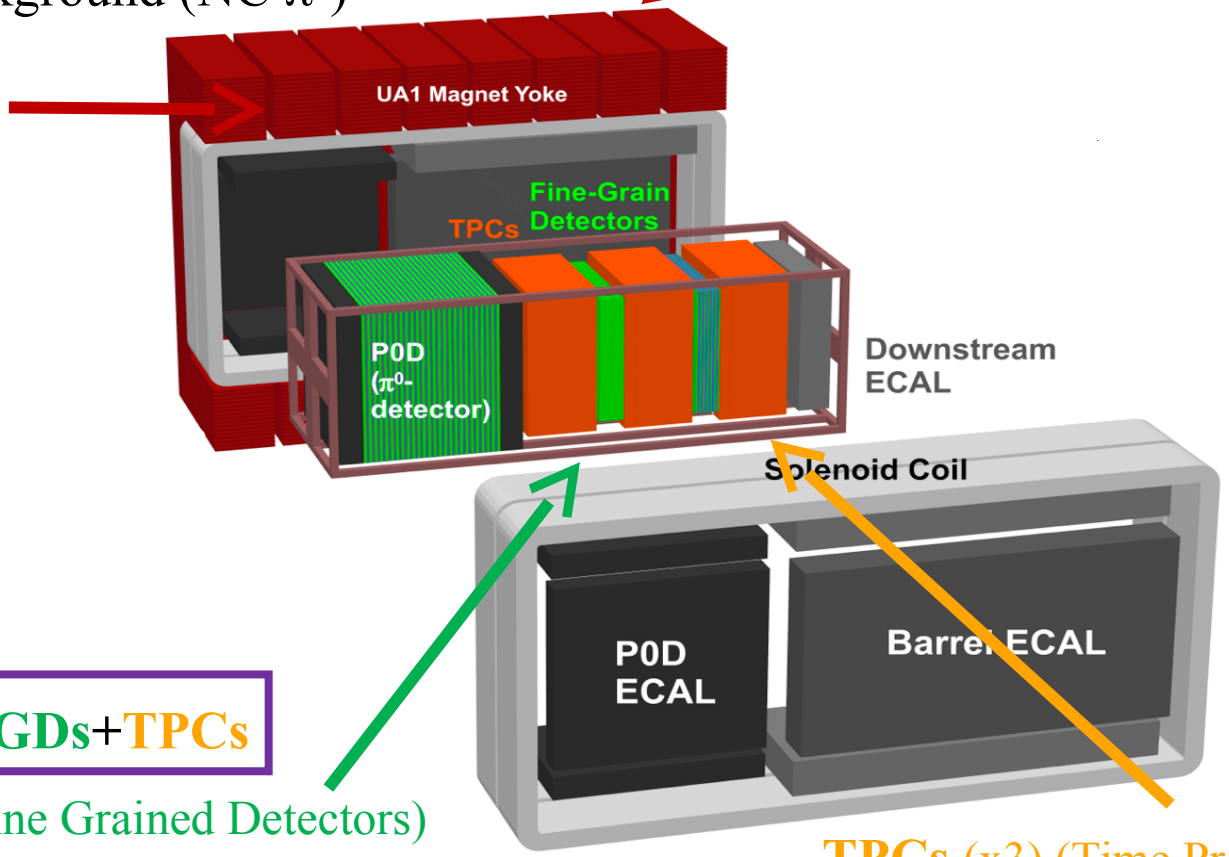
- Off-axis spectrum using CC ν_μ interactions
- Beam ν_e contamination
- Super-K background (NC π^0)

SMRD (Side Muon Range Detector)

- Scintillator planes in magnet yoke
- Detect muons from inner detector
- Momentum measurement

Magnet

- **0.2 T**



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TPCs (x3) (Time Projection Chambers)

- Measure charged particles from FGD/P0D
- Good PID via dE/dx measurement

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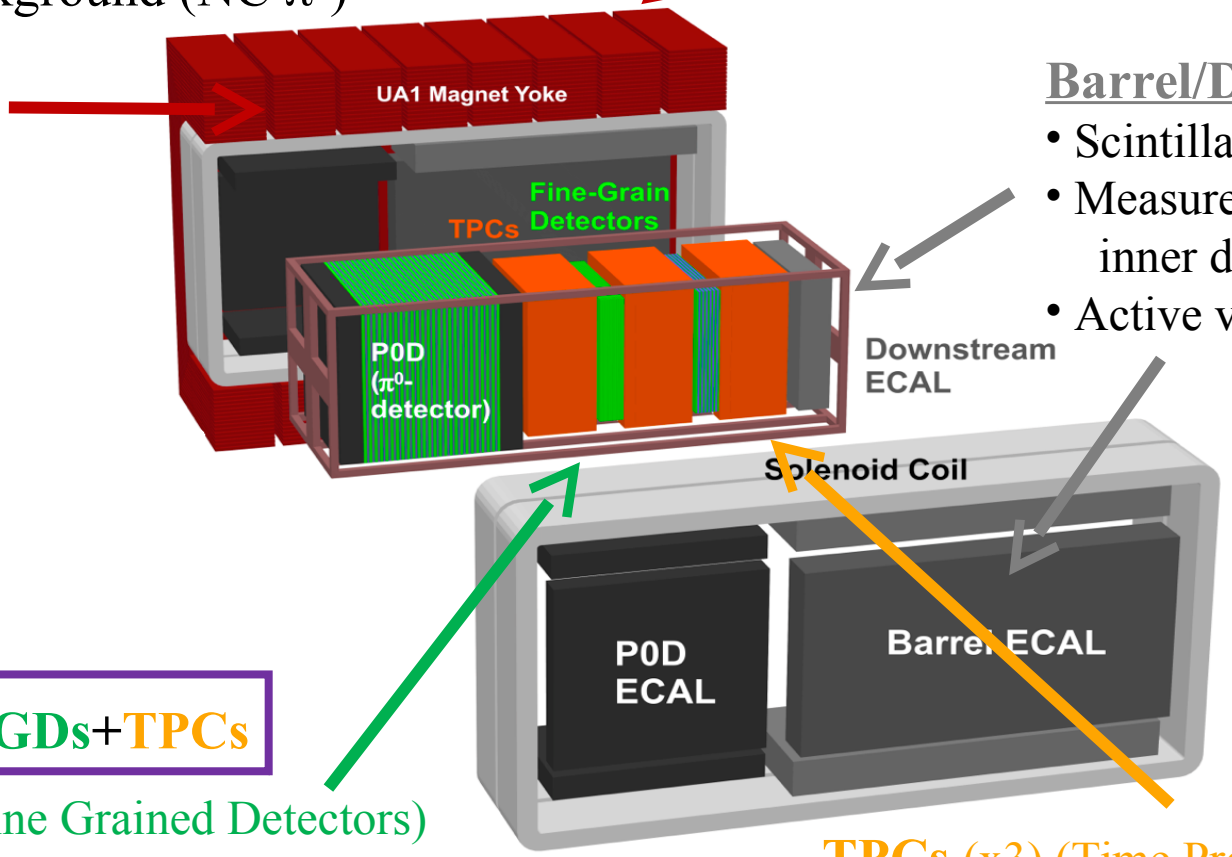
Designed for measurement of

- Off-axis spectrum using CC ν_μ interactions
- Beam ν_e contamination
- Super-K background (NC π^0)

Magnet

- **0.2 T**



SMRD (Side Muon Range Detector)

- Scintillator planes in magnet yoke
- Detect muons from inner detector
- Momentum measurement

Barrel/DownStream ECAL

- Scintillator planes with radiator
- Measure EM showers from inner detector (γ for NC π^0 etc)
- Active veto

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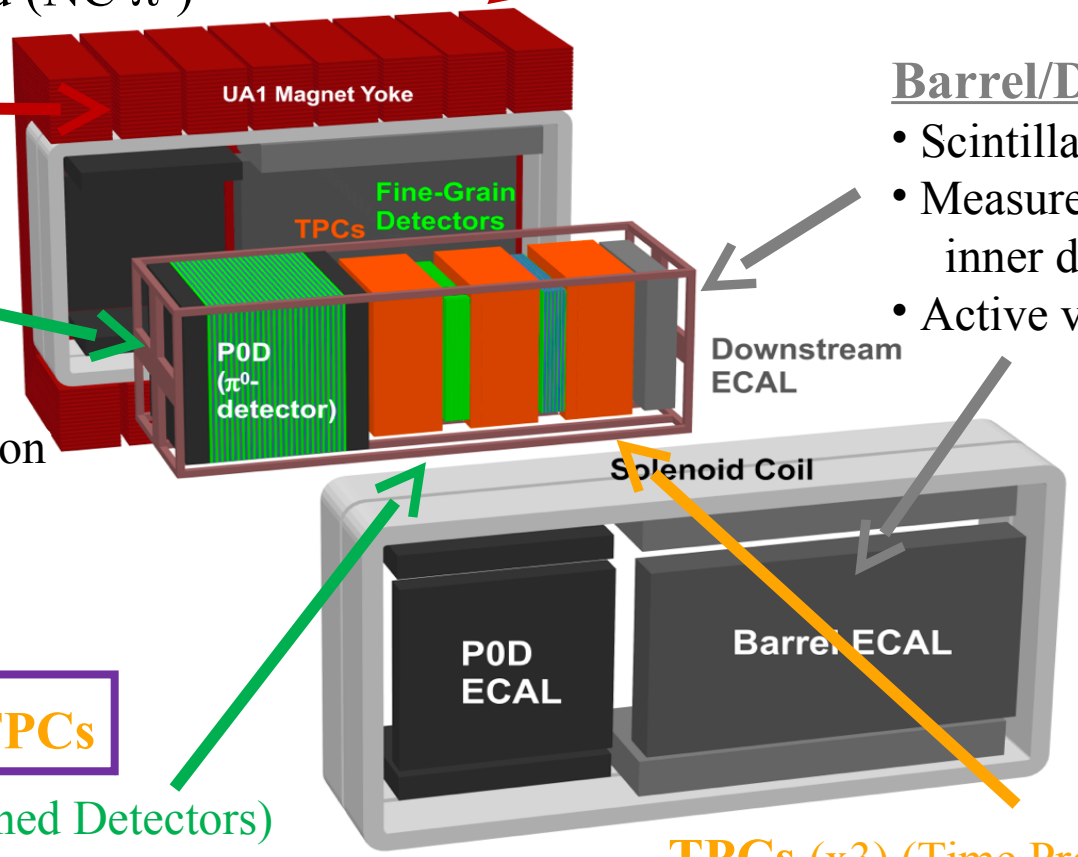
- Off-axis spectrum using CC ν_μ interactions
- Beam ν_e contamination
- Super-K background (NC π^0)

SMRD (Side Muon Range Detector)
- Scintillator planes in magnet yoke
- Detect muons from inner detector
- Momentum measurement

Magnet
- **0.2 T**



Barrel/DownStream ECAL
- Scintillator planes with radiator
- Measure EM showers from inner detector (γ for NC π^0 etc)
- Active veto

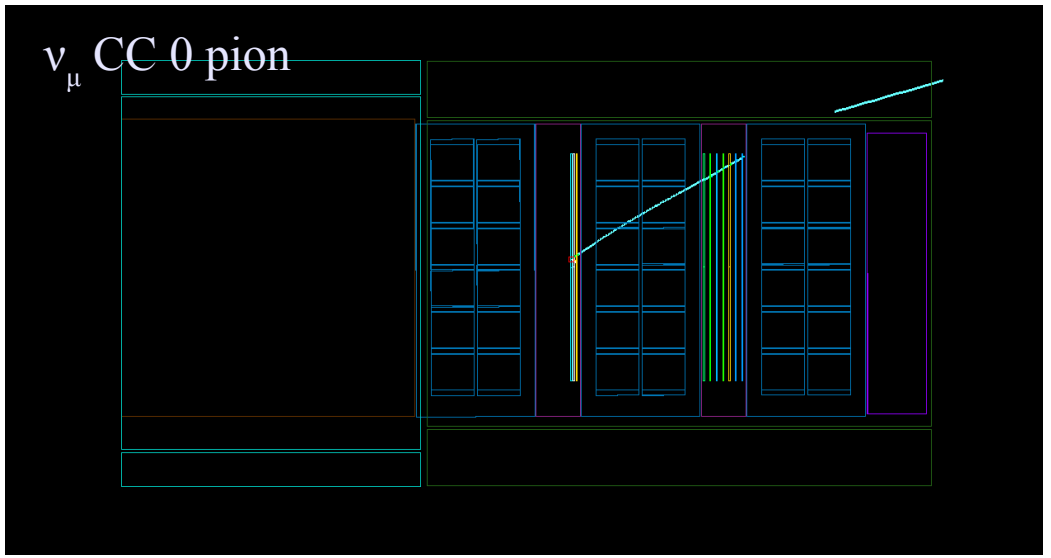
P0D (π^0 Detector)
- Scintillator planes with water & lead/brass layers
- Optimized for π^0 detection
- Mass
  - 15.8 tons w/ water
  - 12.9 tons w/o water

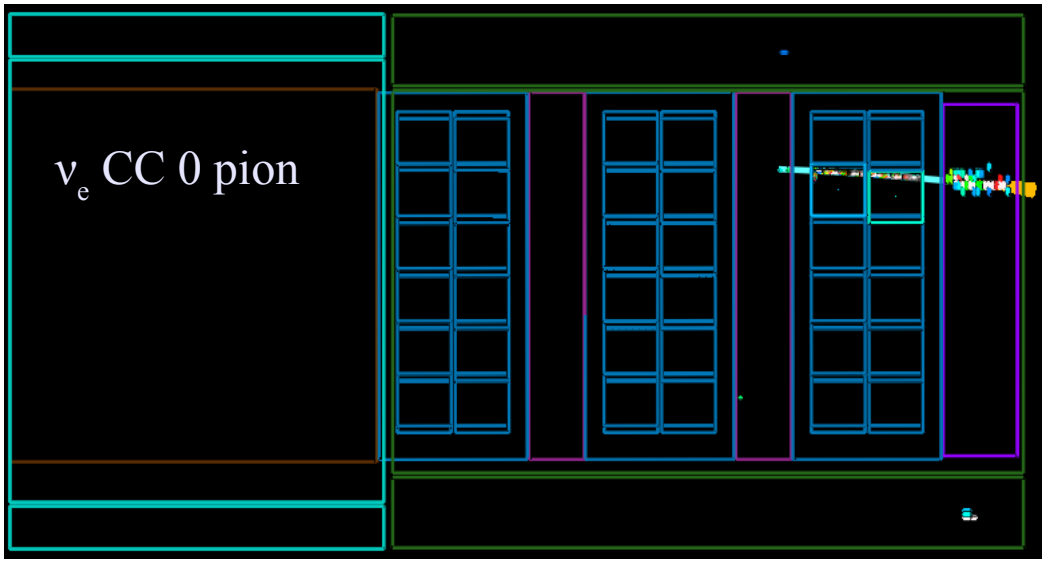
Tracker: FGDs+TPCs

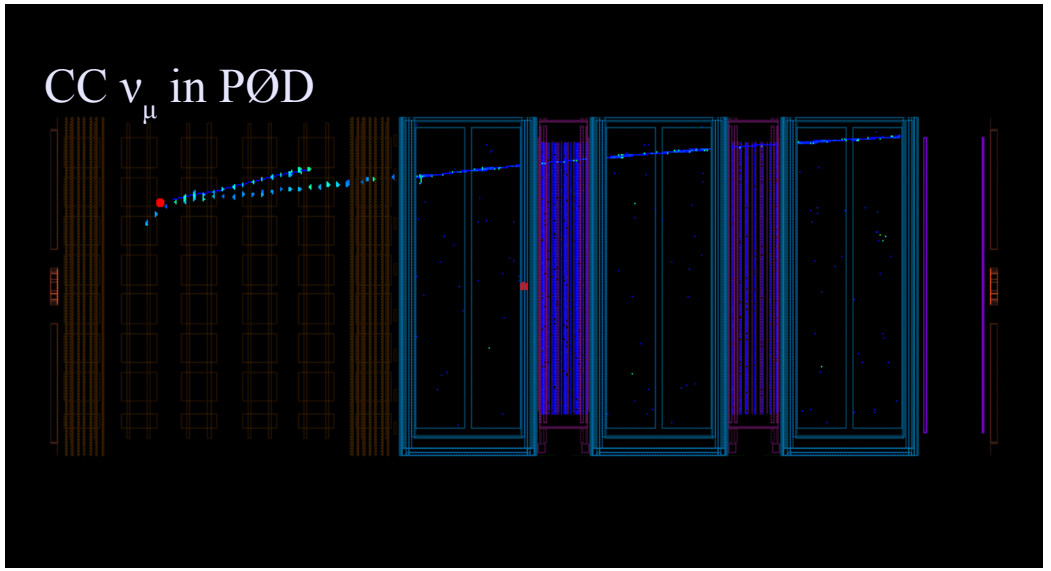
FGDs (x2) (Fine Grained Detectors)
- Provide full active target mass
- FGD1: Scintillator planes ~ 1 ton
  FGD2: Scinti. & water planes ~ 0.5 & 0.5 ton

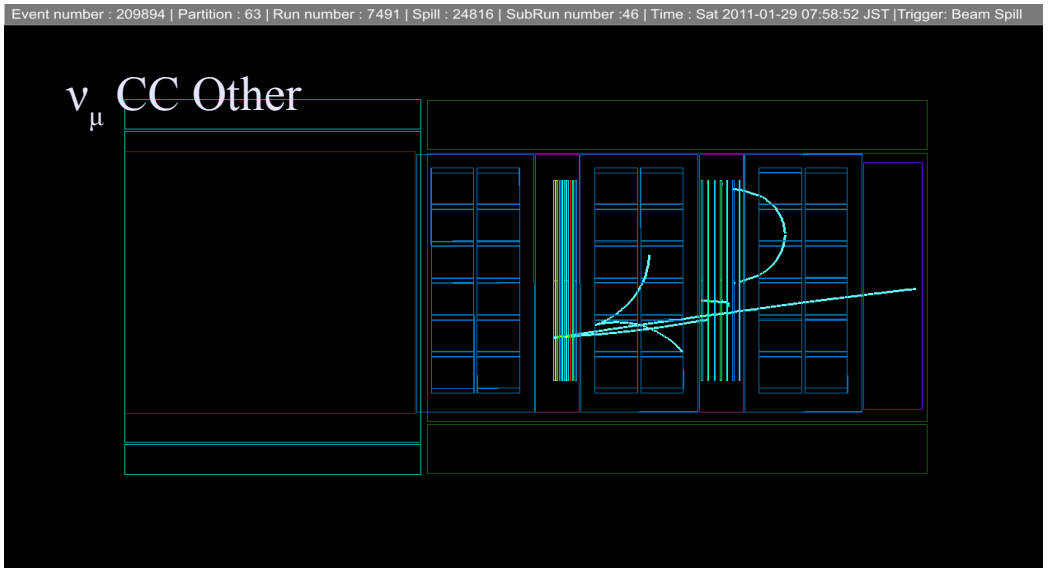
TPCs (x3) (Time Projection Chambers)
- Measure charged particles from FGD/P0D
- Good PID via dE/dx measurement

Typical ND280 Events

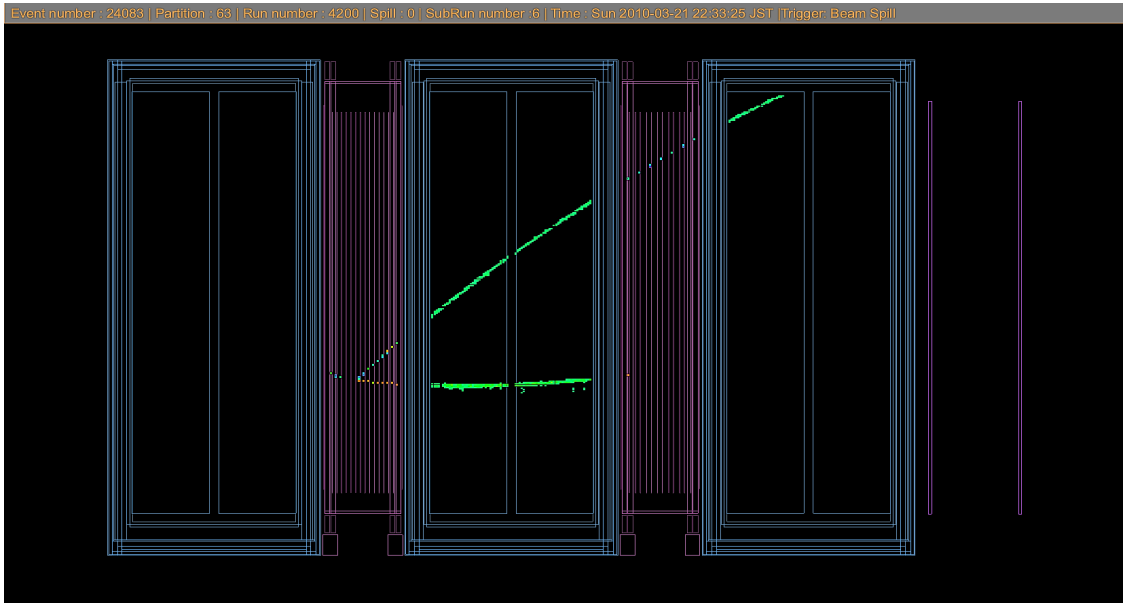








Neutrino Selection in Tracker



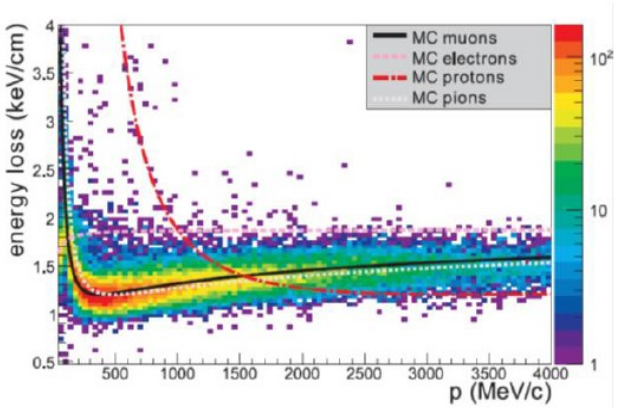
Uses FGDs as a target

Momentum, charge identification and particle identification done using a TPC

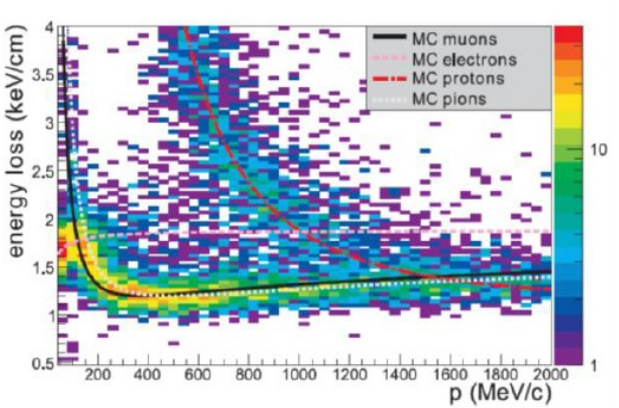
Direction determined using timing

Allows separate identification of protons and pions.

TPC PID for particles from neutrino interactions

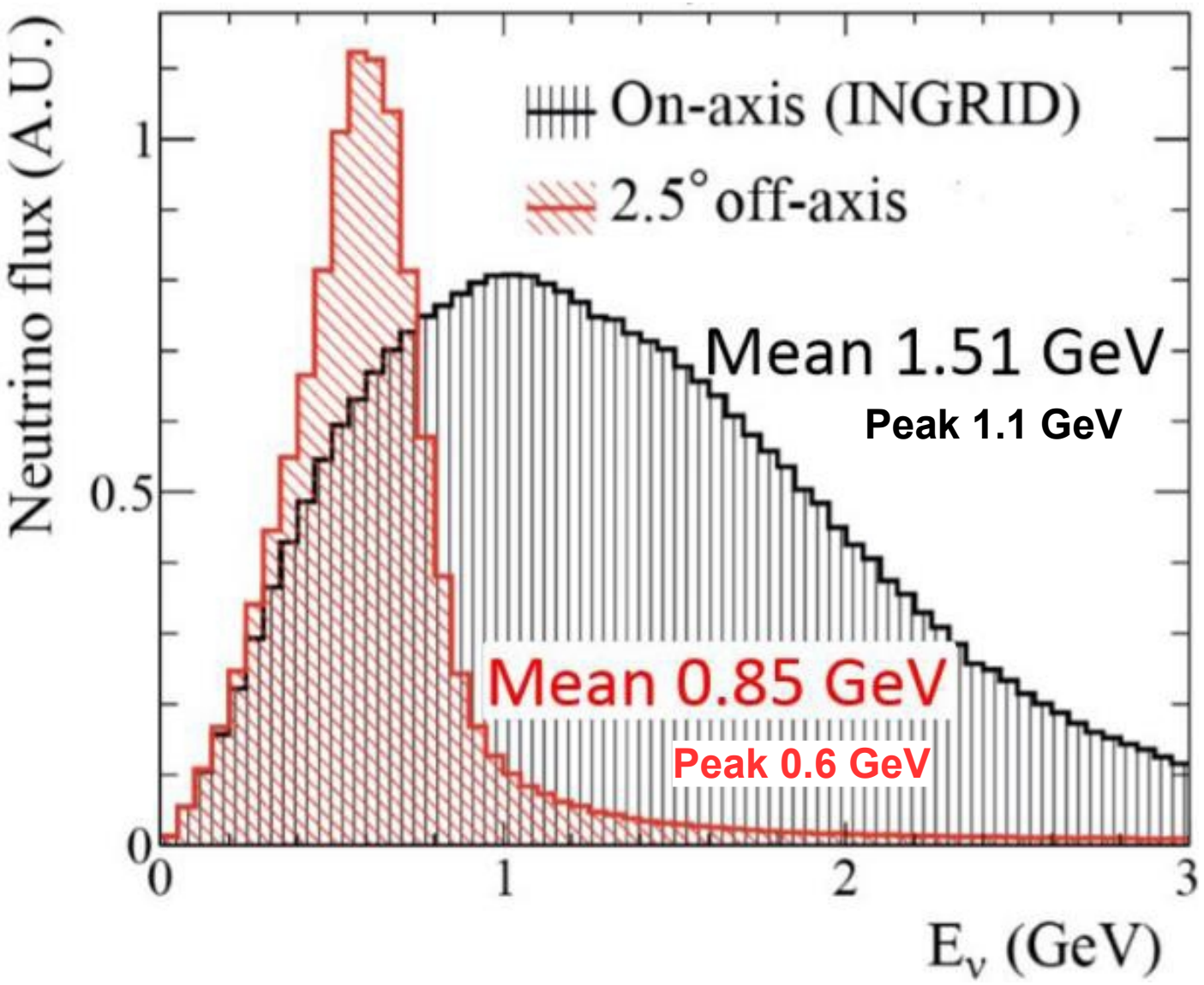


negative



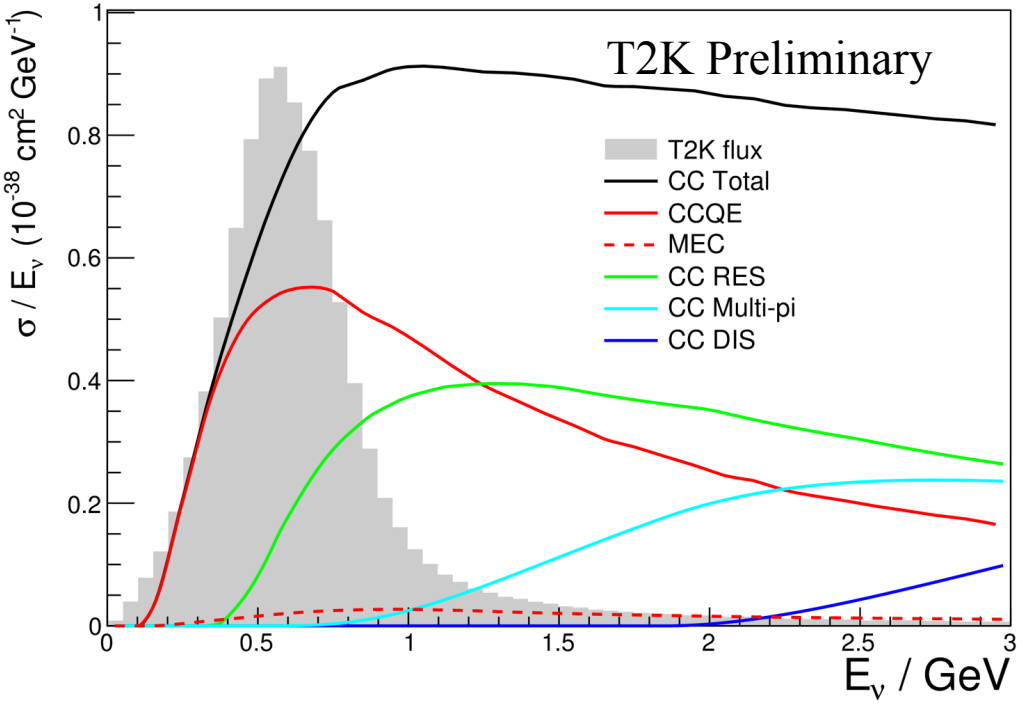
positive

On and Off Axis Spectrum at ND280

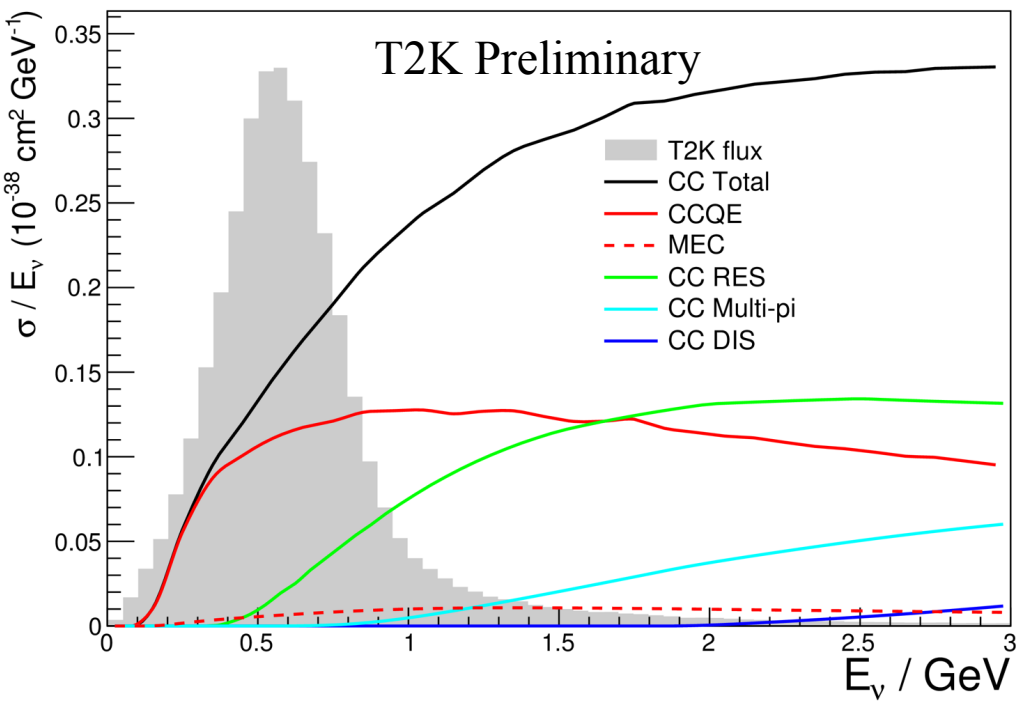


Neutrino and Anti-Neutrino Flux at T2K ND280 Off Axis Detector

Forward Horn Current



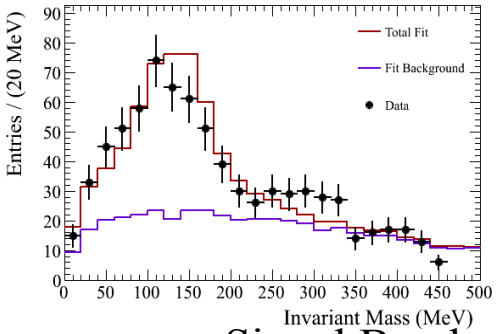
Reverse Horn Current



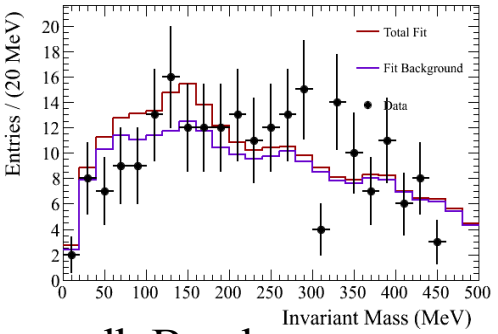
Check of NC π^0 Rate

- Signal defined as
  - One π^0 leaving the target nucleus
  - No charged lepton or charge pion
  - Any number neutrons or protons leaving the target nucleus.
- Fit to the observed π^0 invariant mass peak
  - Constrain background using signal side-bands
    - Invariant mass and muon decay tagged sidebands.
- The ND280 detector was designed to measure interactions on water using statistical subtraction
  - Water In Measurement (data/"post-fit"): 0.944 ± 0.076 (stat) ± 0.231 (sys)
  - Water Out Measurement: 1.107 ± 0.101 (stat) ± 0.316 (sys)
  - Subtracted Measurement: 0.652 ± 0.270 (stat) ± 0.576 (sys)
- Source of systematics has been identified and targeted for reduction

Water in the PØD

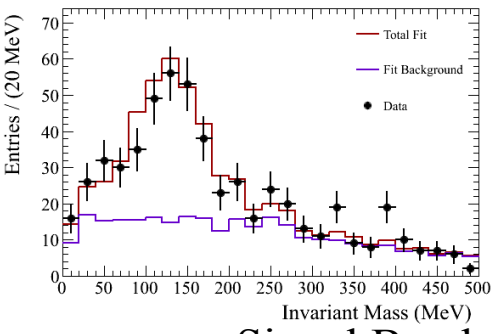


Signal Band

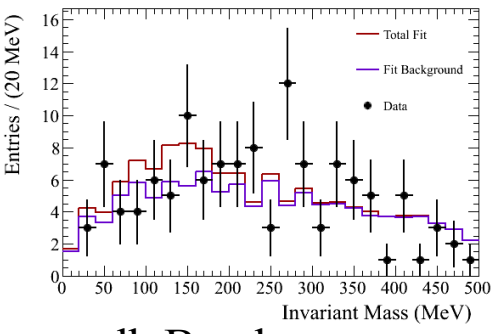


μ-dk Band

Water out of the PØD



Signal Band



μ-dk Band